# Science and Technology for Future Communications Networks


**Cherry A. Murray**
*Physical Sciences Research SVP*

# Science and Technology for Future Communications Networks

## Physical Sciences Research at Bell Labs

- **Overview of Bell Labs and Lucent Technologies**
- **Examples of Current Research in the Physical Sciences**

  **Technologies for Future Optical Networks**

  **(Technologies for  Future Wireless Networks)**

  **Science**

# Bell Labs historical contributions to technology

Lucent Technologies
Bell Labs Innovations

### The Beginning Years: 1869 - 1925

- incorporation of Western Electric
- the telephone
- incorporation of AT&T
- long distance telephony
- wireless transmission of speech
- condenser microphone
- fax service ; electrical sound recording
- Johnson noise
- incorporation of Bell Telephone Labs

### The Era of Vacuum Tube Circuits: 1926 - 1937

- sound motion pictures
- pulse code modulation
- transatlantic radio phone service
- long distance TV transmission
- principle of negative feedback
- wave nature of the electron
- Nyquist's theorum
- artificial larynx
- Galactic radio noise
- high speed motion picture camera
- synthetic speech
- digital computer
- Rad lab radar transmission
- Nobel Prize in Physics to C. Davisson
- cellular telephony

# Bell Labs historical contributions to technology

Lucent Technologies
Bell Labs Innovations

## The Era of Semiconductor Electronics 1947 - 1960

- the transistor
- information theory; error correction
- direct distance dialing
- solar cell; oxide masking; Nb3Sn
- lithographic photoresist
- transatlantic telephone cable
- CW solid state maser
- Nobel Prize in Physics to W. Schockley, J. Bardeen, W. Brattain
- yttrium iron garnet
- Read and Impatt diode oscillators
- laser theory
- Anderson localization
- artificial neuron
- MOSFET
- communications satellite
- bipolar transistor

## The Era of the Laser 1960 - 1976

- Nobel Prize in Physics to C. Townes
- cw laser ( He-Ne )
- Touchtone phone
- superconducting tunneling spectroscopy
- avalanche photodiode
- $CO_2$ laser; YAG laser
- big bang microwave background
- magnetic bubble memories
- ARPANET - first nationwide computer network
- molecular beam epitaxy
- double het semiconductor laser
- UNIX operating system; picturephone
- charged coupled device
- low loss silica fiber < 20dB/km
- optical tweezers; in vivo M R I
- distributed feedback laser
- C programming language
- theory of solitons in optical fiber
- 4ESS fully digital telephony switch

# Bell Labs historical contributions to technology

Lucent Technologies
Bell Labs Innovations

## The Era of Early Fiber Optic Communications 1977 - 1984

- Nobel Prize in Physics to Anderson
- fiber optic communications
- modulation doping
- Nobel Prize in Physics to Penzias and Wilson
- plasma etching of semiconductors
- hexatic phase in condensed matter
- Nobel Prize in Physics to A. Schawlow
- attractor neural networks
- fractional quantum Hall effect
- commercial cellular phones; C++ language
- Bell System Divestiture -> RBOC's, 1/4 of Bell Labs Research spins off into Bell Core; 3/4 remains with AT&T Long Lines: renamed AT&T Bell Labs

## The Competitive Era Begins: AT&T Bell Labs 1984 - 1996

- gravitational lensing, dark mass distribution in the universe
- semiconductor nanocrystals
- squeezed states of light; laser cooling
- YBCO 1:2:3 composition
- single electron transistor
- smart card
- digital cellular system
- functional MRI
- HDTV
- fault tolerant software; videophone
- sol gel process for high quality fiber
- quantum cascade laser
- quantum computation error correction
- Nobel Prize in Physics to D. Osheroff

# Bell Labs historical contributions to technology

Lucent Technologies
Bell Labs Innovations

## Lucent Technologies First Years: 1997 - 2000

- AT&T Trivestiture --> AT&T, 1/4 of Bell Labs stays with AT&T Labs; NCR; Lucent Technologies IPO, 3/4 of Bell Labs Research goes with Lucent
- Bell Labs China established
- multiwavelength semiconductor laser
- 2 - photon imaging of neurons in brain
- quantum search algorithm
- Nobel Prize in Physics to S. Chu
- toehold catalysis of DNA
- Nobel Prize in Physics to D. Tsui, H. Stormer and R. Laughlin
- 1022 channel transmission on 1 fiber
- vertical replacement gate transistor
- fully functional InP 40GHz fiber optic communications transceiver chip set
- free space optical crossconnects using MEMS mirror array
- all plastic flexible transistors to power electronic paper
- DNA tweezers
- 320 Gb/s data transmission in optical fiber
- Lucent Technologies spins out Avaya Systems - 10 researchers go to Avaya Research
- Bell Labs Research China formed

# Bell Labs historical contributions to technology

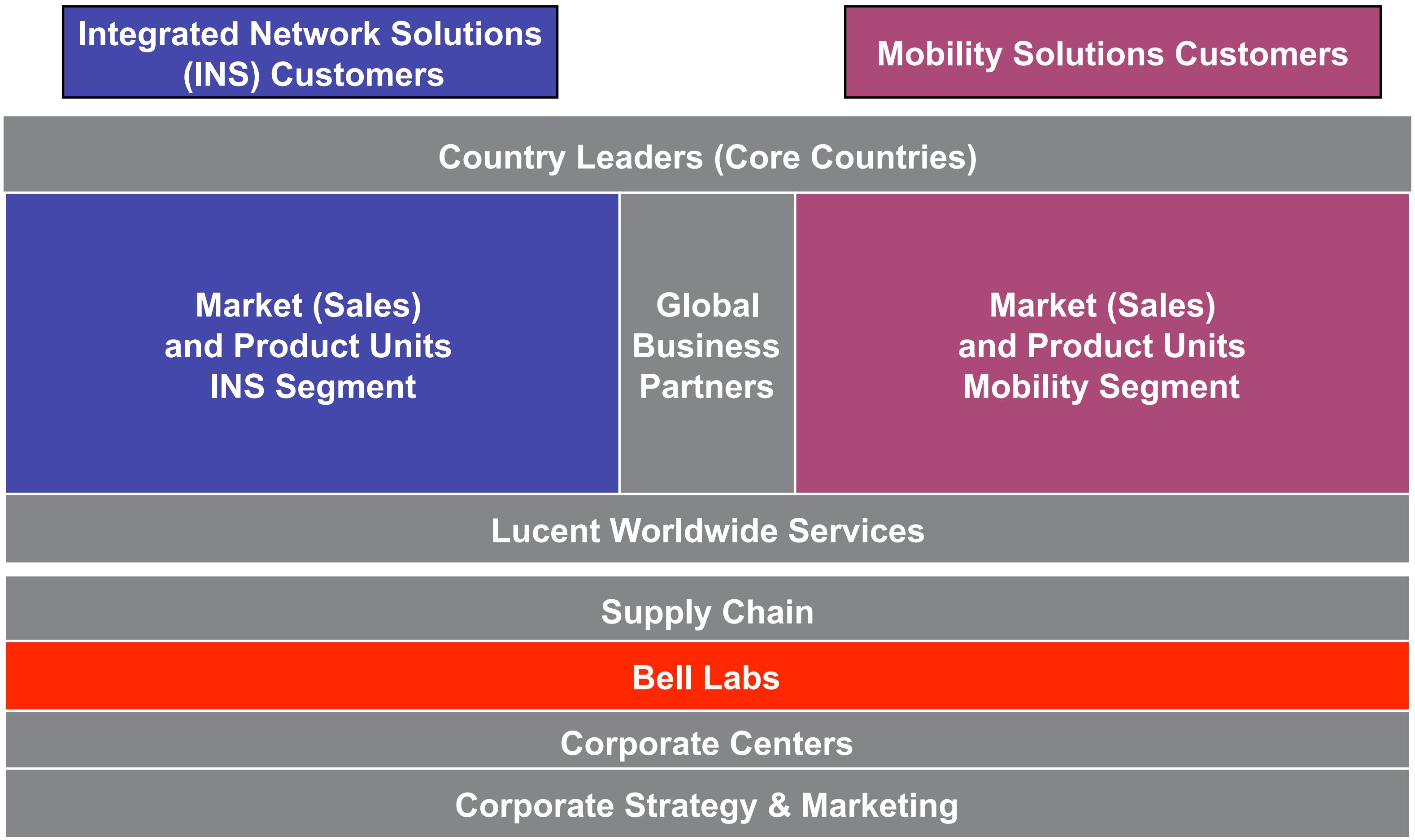
Lucent Technologies
Bell Labs Innovations

**Bell Labs, Lucent Technologies 2001- 2002**

- Casimir effect measured - actuation of MEMS by vacuum fluctuations
- optical phase conjugation at 160Gb/s data transmission
- 3.6 Tb/s wavelength division multiplexing on a single fiber
- limits to nonlinear optical channel capacity; limits to random matrix cellular channels
- tripolarized antennas for increase in channel capacity with scattering
- observation of persistent neural activity - a new form of network dynamics
- unlocked self-timed state transitions in the firing of multiple neurons
- complete RF solution using single-chip radio on silicon with direct-conversion
- first silicon-integrated radio front-end for base stations applications
- transmitted 860 Gb/s solitons over 7500 km
- first physics-based network capacity vs coverage wireless network optimization tool
- super distributed home location register for wireless global roaming
- Ultra long haul transmission of 40G optical pulses for 4000km
- Lucent Technologies sells off Power Systems and spins out Agere Systems - 2/3 of Bell Labs Research remains with Lucent, 1/3 goes as Agere Research; Optical Fiber Solutions Business sold - 45 researchers go to Furakawa. Lucent Technologies focuses on service intelligent networks for major service providers; and reaffirms its commitment to Bell Labs as an innovation engine.

**Bell Labs Research continues its tradition of fundamental and applied research relevant to and inventing the future of communications technologies**

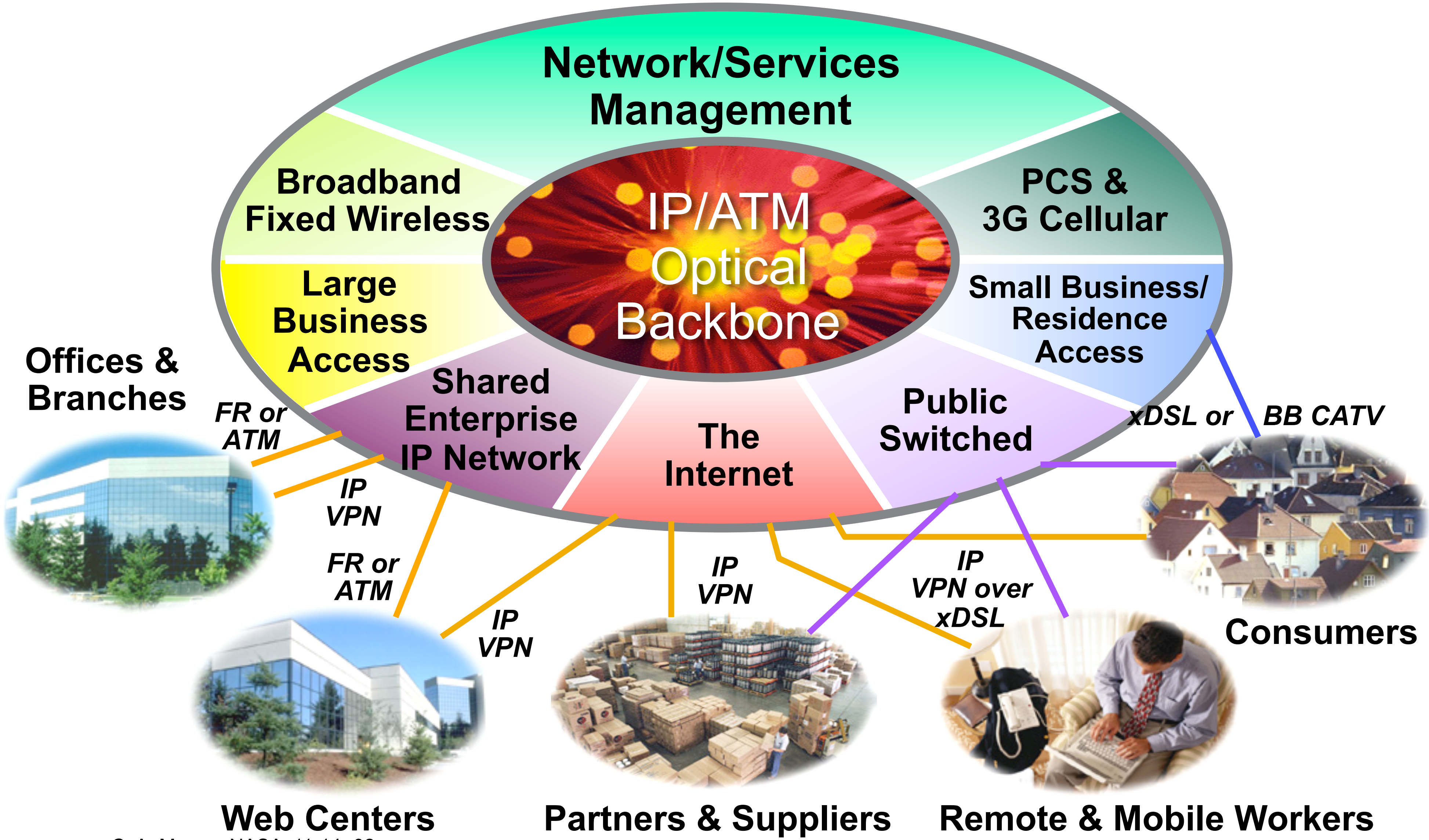
New Business Model for Lucent Technologies Oct 2001 - consistent with new market dynamics - focus on the major telecommunications service providers, in wireline and wireless segments, as the telecomm industry is undergoing 'de - integration' and consolidation




Bell Labs is the R&D arm of Lucent . Bell Labs consists of development in the segments ( 10000 people ) as well as corporate funded Bell Labs Research and BU funded Bell Labs Advanced Technologies ( 1200 people )

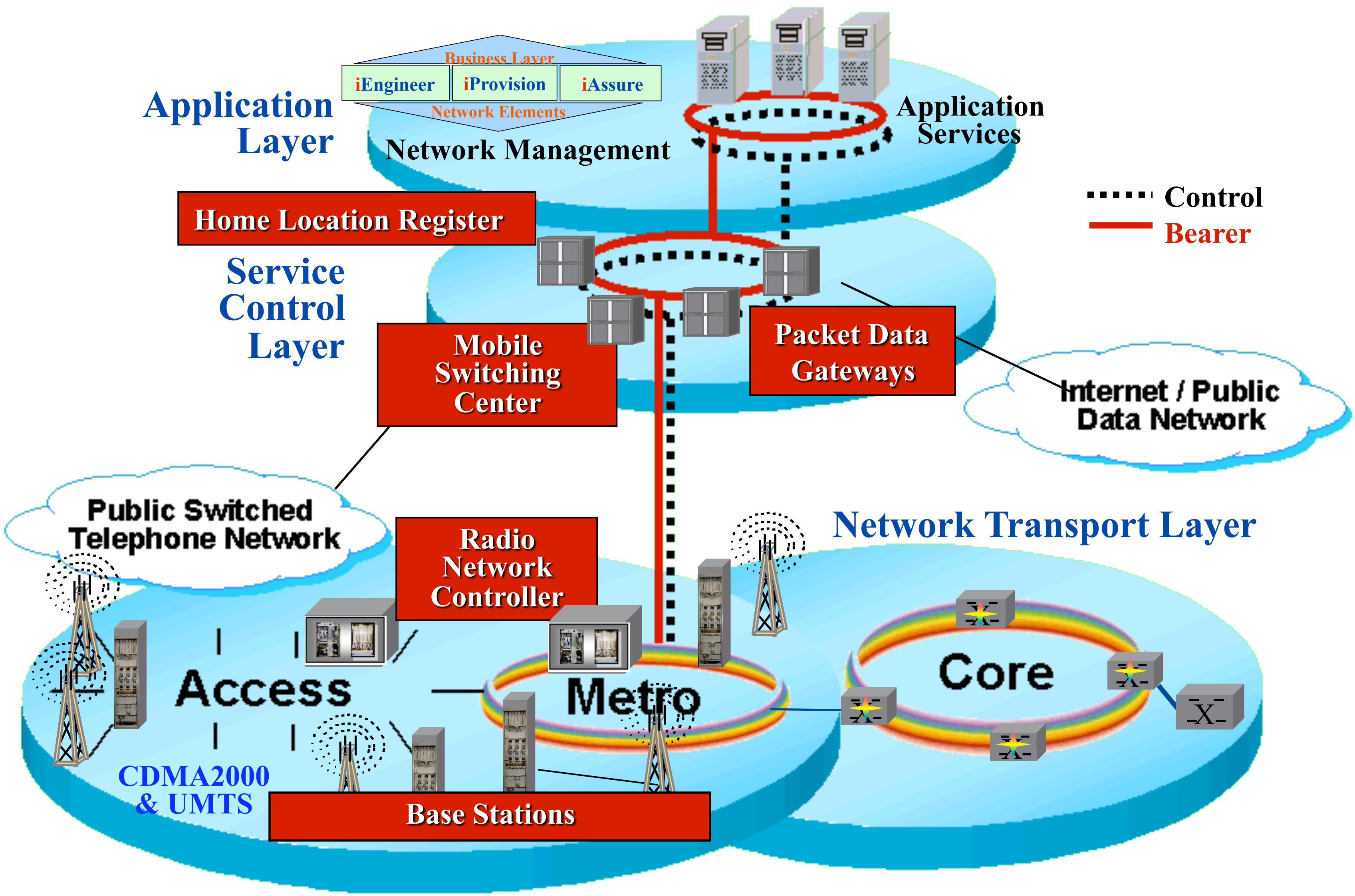
C. A. Murray, NASA 11-14 -02

Lucent Technologies Products : broadband data and communications networks, broadband mobile internet infrastructure and network management systems and services for large service providers

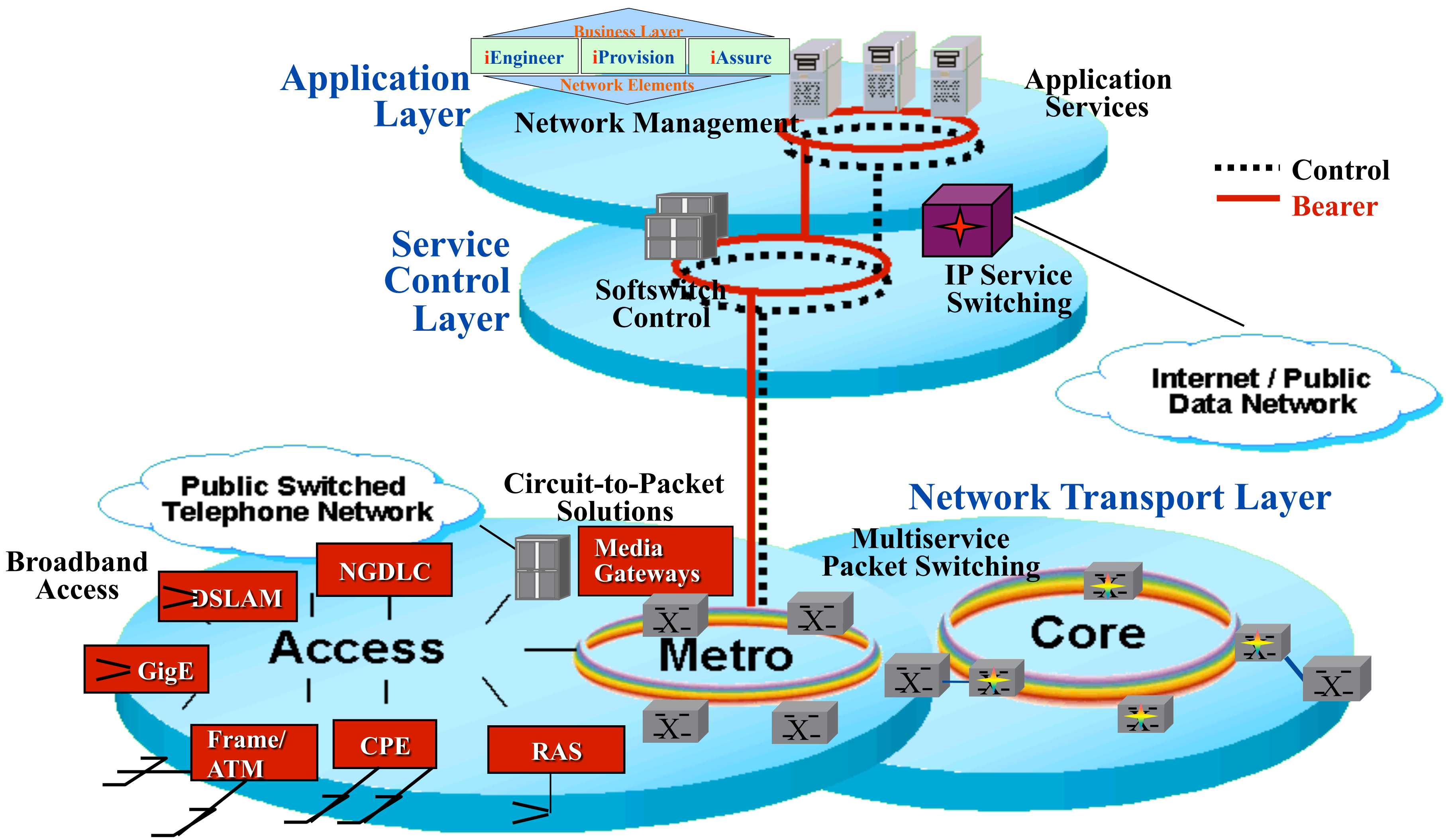



C. A. Murray, NASA 11-14 -02

# Wireless communication network architecture today -> transition from 2G to 3G systems



# Wireline communication network architecture today -> transition to all optical networking and MPLS for data



Wireless

# RESEARCH

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**President,**
**Bell Labs Research and Advanced Technologies**

*Jim Galiano*
Assistant to the President

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*Rod Alferness*
SVP
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Photonics Research Lab
Directors: Andy Chraplyvy
Randy Giles
Alice White
Martin Zirngibl

*Dave Bishop*
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Communications Subsystems
Research Lab
Directors: Susanne Arney
Y-K Chen
John Gates
Lou Manzione

*Vijay Kumar*
Director
Optical Networking
Research Division

*Ed Szurkowski*
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Research Center
Director: Mark Cardillo

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Gerard Holzmann
Howard Trickey

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Markus Hoffmann
Joe Olive

*Krishan Sabnani*
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TV Lakshman
Scott Miller
Sanjoy Paul
Thomas Woo

*David Lee*
VP
BL Research China

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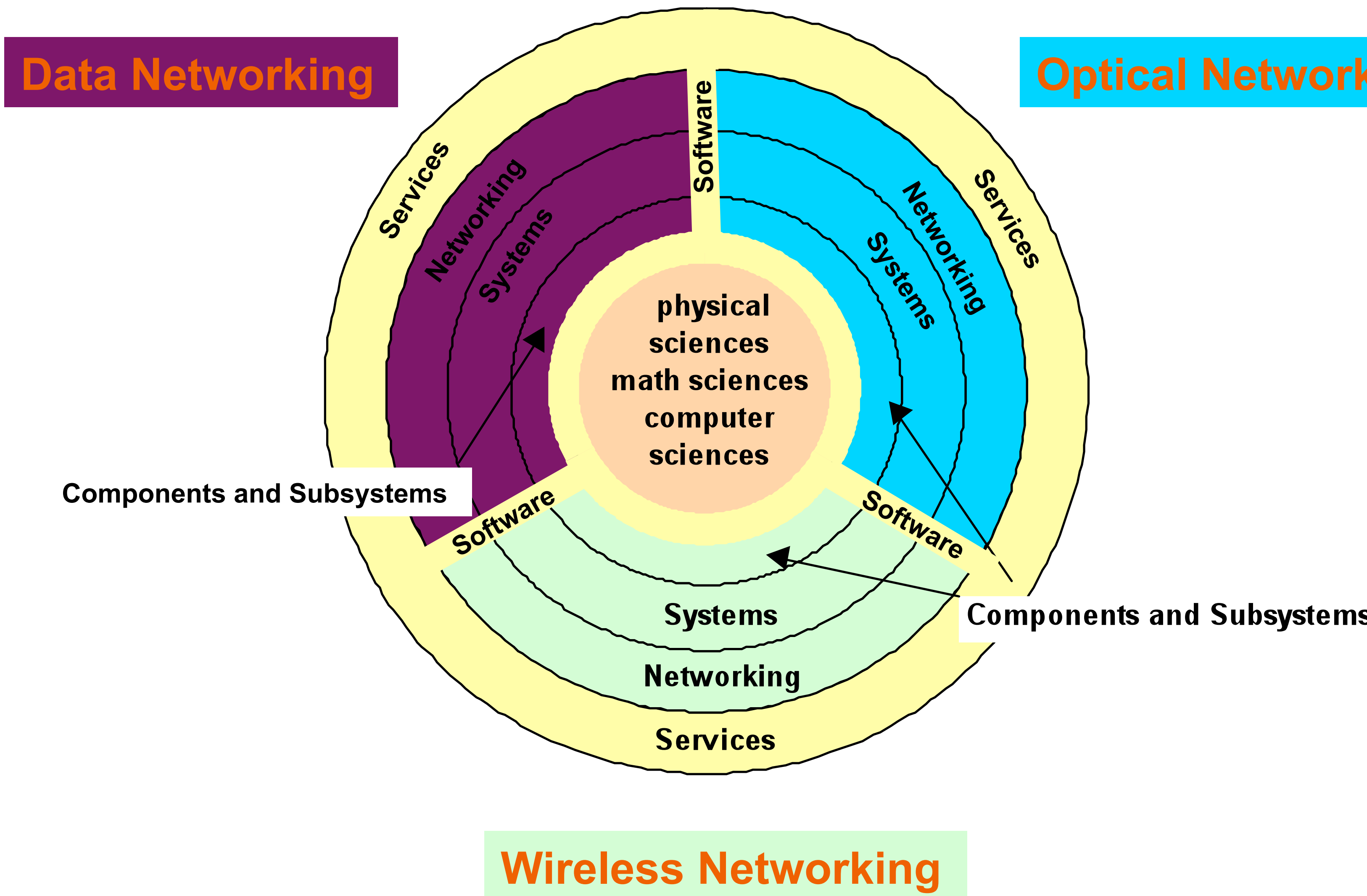
# Bell Labs Research Science and Technology Areas

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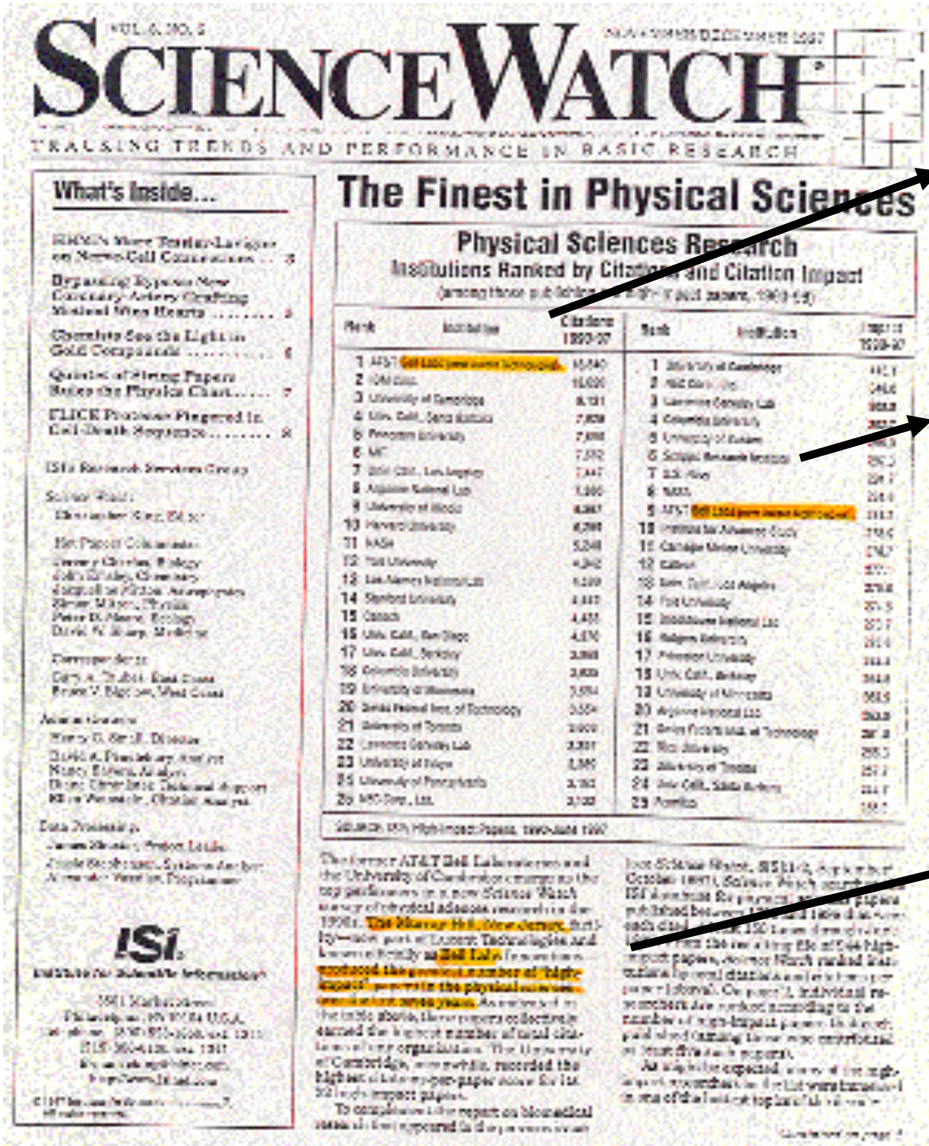
# Bell Labs, Lucent Technologies Headquarters, Murray Hill, NJ

## Bell Labs Research is #1 in physical science citations - 1990's


SCIENCE WATCH

TRACKING TRENDS AND PERFORMANCE IN BASIC RESEARCH

What's Inside...

The Finest in Physical Sciences

Physical Sciences Research

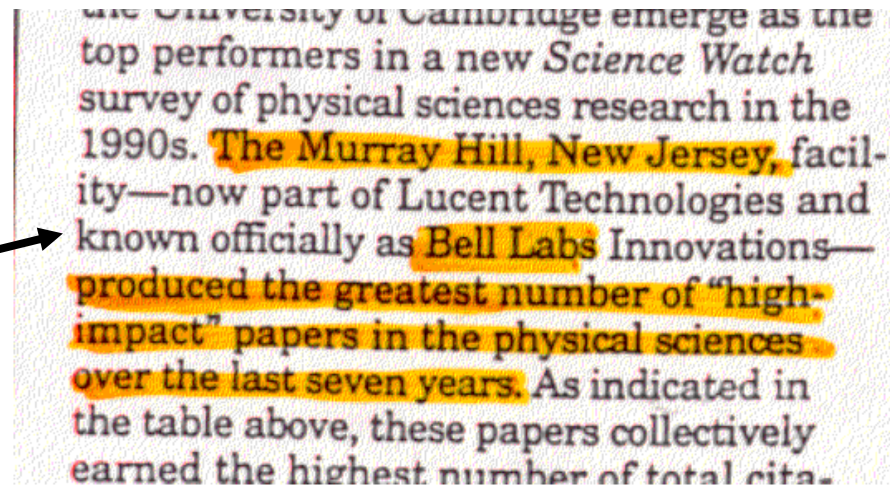
Institutions Ranked by Citations and Citation Impact

**Total Number of Citations:**

| | |
|---|---|
| 1.AT&T Bell Labs (now Lucent Technologies) | 18,840 |
| 2.IBM Corp | 13,020 |

**Average Citations per paper:**

| | |
|---|---|
| 8 NASA | 291.6 |
| 9 AT&T Bell Labs (now Lucent Technologies) | 281.2 |
| 10 Institute for advanced Study | 278.9 |


the University of Cambridge emerge as the top performers in a new *Science Watch* survey of physical sciences research in the 1990s. The Murray Hill, New Jersey, facility—now part of Lucent Technologies and known officially as Bell Labs Innovations—produced the greatest number of "high-impact" papers in the physical sciences over the last seven years. As indicated in the table above, these papers collectively earned the highest number of total cita-

AN MIT ENTERPRISE TECHNOLOGY REVIEW

## The TR Patent Scorecard 2001

May 2001

*We ranked companies in key industries according to the quality and quantity of their patents. Here are 150 of the world's top firms.*

### Telecommunications

| Company | Technological Strength/Rank 2000 | Technological Strength/Rank '95-'99 * | Number of Patents 2000 | Number of Patents '95-'99 * | Current Impact Index 2000 | Current Impact Index '95-'99 * | Science Linkage 2000 | Science Linkage '95-'99 * | Technology Cycle Time 2000 | Technology Cycle Time '95-'99 * |
|---|---|---|---|---|---|---|---|---|---|---|
| Lucent Technologies | 2485/1 | 1701/2 | 1445 | 881 | 1.72 | 1.93 | 1.31 | 1.78 | 5.4 | 5.4 |
| Motorola | 2035/2 | 2148/1 | 1241 | 1193 | 1.64 | 1.80 | 0.63 | 0.76 | 5.4 | 5.5 |
| Ericsson Telephone | 1651/3 | 714/3 | 775 | 320 | 2.13 | 2.23 | 0.99 | 1.32 | 5.2 | 5.8 |
| BCE | 1024/4 | 369/5 | 472 | 179 | 2.17 | 2.06 | 0.89 | 1.09 | 4.8 | 4.9 |
| AT&T | 875/5 | 566/4 | 343 | 135 | 2.55 | 4.18 | 1.07 | 1.12 | 4.6 | 4.8 |
| Nokia | 630/6 | 259/8 | 306 | 163 | 2.06 | 1.59 | 0.49 | 0.53 | 5.3 | 5.3 |
| Alcatel | 478/7 | 319/7 | 423 | 285 | 1.13 | 1.12 | 0.79 | 1.06 | 6.4 | 6.7 |
| Qualcomm | 451/8 | 350/6 | 111 | 63 | 4.06 | 5.56 | 0.71 | 1.47 | 6.7 | 6.4 |
| Verizon Communications | 375/9 | 147/11 | 93 | 74 | 4.03 | 1.99 | 0.73 | 1.75 | 5.9 | 6.1 |
| Cabletron Systems | 253/10 | 116/12 | 41 | 17 | 6.18 | 6.98 | 2.00 | 2.39 | 5.2 | 4.5 |
| MCI Worldcom | 216/11 | 193/10 | 82 | 63 | 2.64 | 3.05 | 0.99 | 1.13 | 4.7 | 4.6 |
| Nippon Telegraph & Telephone | 168/12 | 204/9 | 127 | 120 | 1.32 | 1.70 | 2.04 | 2.15 | 4.6 | 5.0 |
| Ciena | 109/13 | 30/17 | 26 | 6 | 4.18 | 4.61 | 1.73 | 1.97 | 5.0 | 4.1 |
| JDS Uniphase | 100/14 | 57/15 | 52 | 36 | 1.93 | 1.61 | 2.21 | 1.31 | 7.1 | 7.5 |
| Qwest Communications International | 97/15 | 105/13 | 29 | 33 | 3.33 | 3.16 | 0.34 | 1.13 | 4.1 | 5.0 |
| British Telecommunications | 95/16 | 78/14 | 70 | 60 | 1.35 | 1.31 | 3.36 | 3.54 | 6.5 | 5.9 |
| BellSouth | 92/17 | 52/16 | 27 | 19 | 3.42 | 2.80 | 0.30 | 0.45 | 5.1 | 5.7 |

**Lucent Technologies is #1 in quality of telecommunications patent portfolio, 2001**

**Bell Labs Raman Amplifier patent is rated one of the top 5 important patents in all fields**

## The TR Patent Scorecard 2002

May 2002

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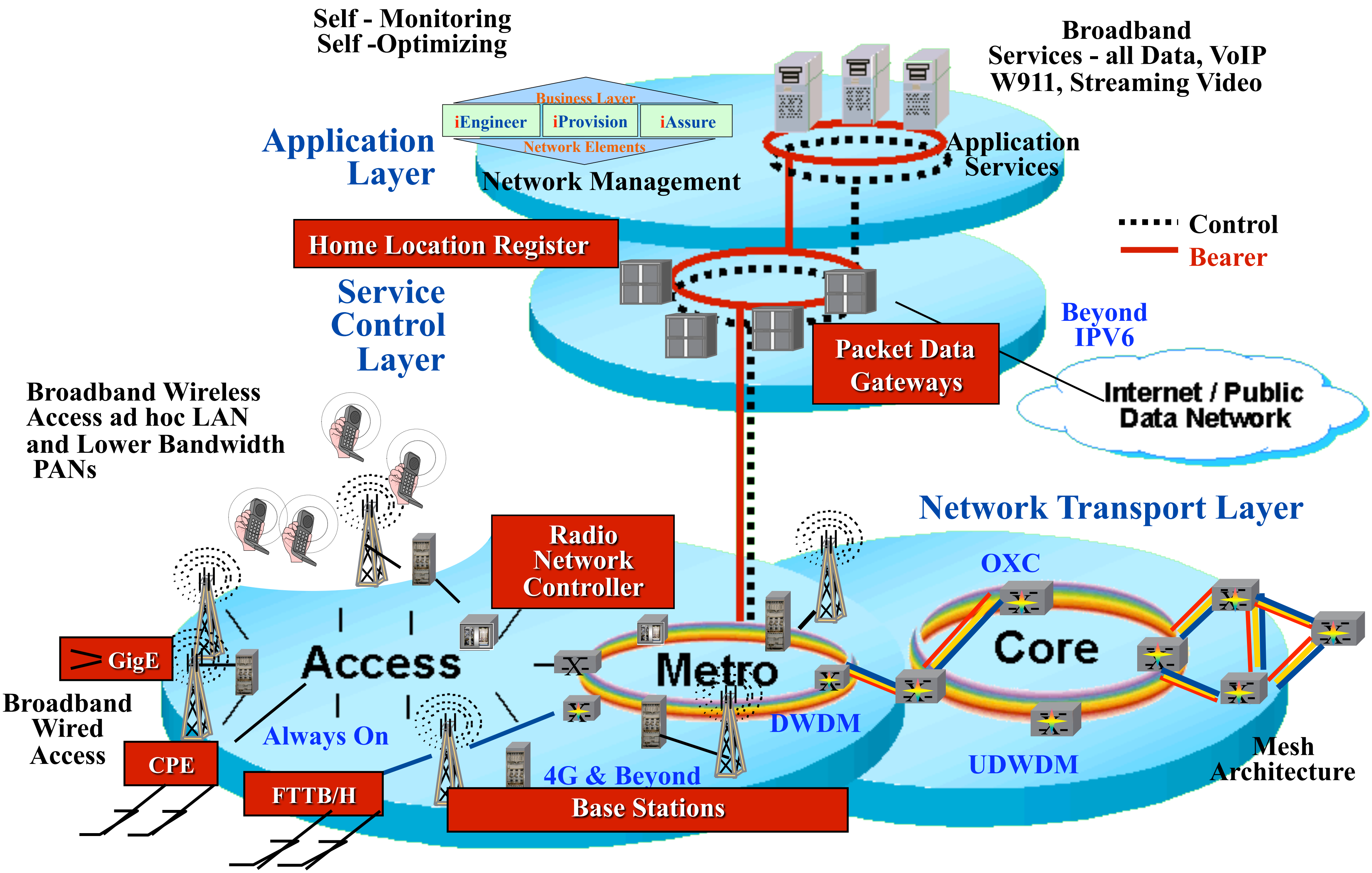
### Telecommunications

| COMPANY[1] | TECHNOLOGICAL STRENGTH/RANK 2001 | TECHNOLOGICAL STRENGTH/RANK 1996-2000 AVERAGE[2] | NUMBER OF PATENTS 2001 | NUMBER OF PATENTS 1996-2000 AVERAGE[2] | CURRENT-IMPACT INDEX 2001 | CURRENT-IMPACT INDEX 1996-2000 AVERAGE[2] | SCIENCE LINKAGE 2001 | SCIENCE LINKAGE 1996-2000 AVERAGE[2] | TECHNOLOGY CYCLE TIME 2001 | TECHNOLOGY CYCLE TIME 1996-2000 AVERAGE[2] |
|---|---|---|---|---|---|---|---|---|---|---|
| Lucent Technologies (U.S.) | 2,531/1 | 1,946/2 | 1,633 | 1,046 | 1.55 | 1.86 | 1.22 | 1.60 | 5.4 | 5.4 |
| Ericsson (Sweden) | 1,369/2 | 999/3 | 782 | 454 | 1.75 | 2.20 | 0.88 | 1.21 | 5.5 | 5.6 |
| Motorola (U.S.) | 1,210/3 | 2,144/1 | 829 | 1,232 | 1.46 | 1.74 | 1.28 | 0.81 | 5.2 | 5.5 |
| Nortel Networks (Canada) | 938/4 | 543/5 | 507 | 255 | 1.85 | 2.13 | 0.72 | 1.06 | 4.5 | 4.8 |
| AT&T (U.S.) | 654/5 | 602/4 | 304 | 177 | 2.15 | 3.40 | 1.23 | 1.06 | 4.7 | 4.6 |
| Nokia (Finland) | 639/6 | 368/8 | 355 | 208 | 1.80 | 1.77 | 0.32 | 0.55 | 5.3 | 5.2 |
| Qualcomm (U.S.) | 589/7 | 395/6 | 184 | 81 | 3.20 | 4.88 | 0.78 | 1.22 | 6.3 | 6.6 |
| Alcatel (France) | 557/8 | 370/7 | 472 | 330 | 1.18 | 1.12 | 0.71 | 0.98 | 6.1 | 6.5 |
| Verizon Communications (U.S.) | 370/9 | 224/9 | 98 | 85 | 3.78 | 2.64 | 1.56 | 1.50 | 6.3 | 6.0 |
| JDS Uniphase (U.S.) | 264/10 | 121/13 | 120 | 67 | 2.20 | 1.80 | 3.17 | 2.28 | 6.5 | 6.8 |
| WorldCom (U.S.) | 156/11 | 209/10 | 73 | 75 | 2.14 | 2.79 | 0.70 | 1.16 | 5.2 | 4.6 |
| Nippon Telegraph and Telephone (Japan) | 154/12 | 203/11 | 126 | 126 | 1.22 | 1.61 | 1.82 | 2.13 | 5.2 | 4.9 |
| British Telecommunications (U.K.) | 141/13 | 82/15 | 95 | 62 | 1.48 | 1.32 | 2.91 | 3.38 | 6.1 | 6.1 |
| Sprint (U.S.) | 111/14 | 46/16 | 29 | 12 | 3.82 | 3.80 | 11.41 | 5.78 | 6.8 | 5.6 |
| Qwest Communications International (U.S.) | 109/15 | 117/14 | 43 | 36 | 2.54 | 3.26 | 0.19 | 0.90 | 4.2 | 4.9 |
| Science Applications International (U.S.) | 108/16 | 154/12 | 38 | 49 | 2.84 | 3.15 | 1.34 | 2.44 | 5.5 | 5.6 |

**Lucent Technologies is #1 in quality of telecommunications patent portfolio, 2002**

**Bell Labs Wireless Communications Systems Employing Multi-Element Antennas is rated one of the top 5 important patents in all fields**

# Commercial network architecture vision 2015 – the broadband mobile Internet – all packet, with optical core – intelligence moving to the network edge

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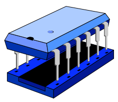
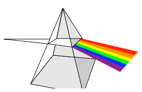
# The Information Age

Six technologies are the drivers of phenomenal growth of information and communications infrastructure that accounts for 5-15% of the GDP and in addition has enabled an increase in US non-farm productivity – these trends and deregulation have caused incredible churn in the industry.

## Technology



- Integrated Circuits

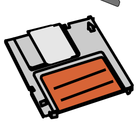


- Photonics

- Storage

- Displays

- Wireless



- Software

## Trend

X2 in density/speed every 18-24 months

X2 in transmission capacity every year

X2 in storage density every 9 months

X2 in pixels every 2 years

X10 - X1000 in channel capacity in 5 years

X2 in operating system size every 2 years

**Physical Sciences research enables all these key technologies except software**

C. A. Murray, NASA 11-14 -02

# Materials needs in future communications networks

- **Electronics** - higher speed ballistic devices, lower voltage, higher power & breakdown voltage, massive integration, new materials

- **Photonics** - reduced nonlinearity and optical dispersion fiber, broadband amplifers, integrated photonic circuits, optical buffers, wavelength changers

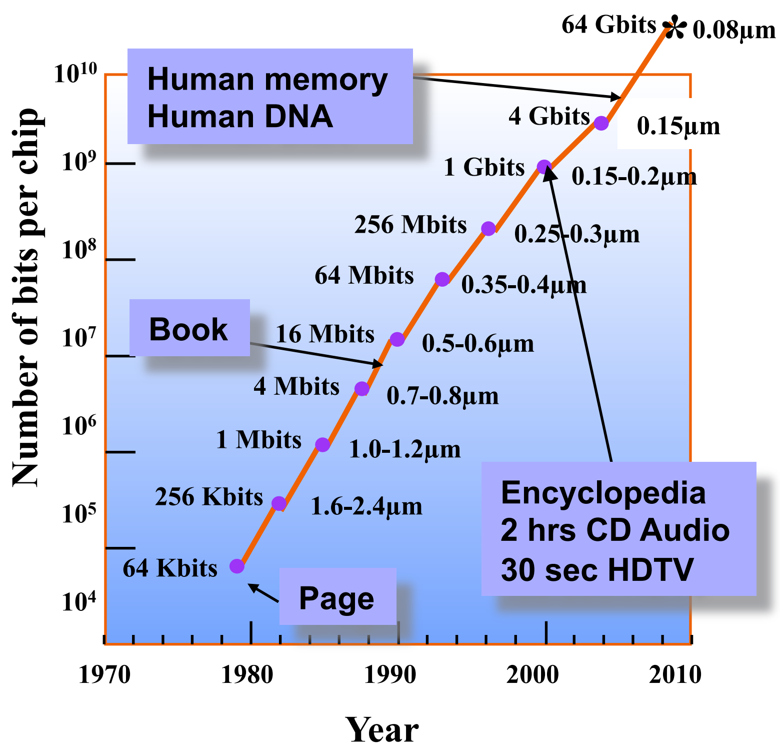
- **Wireless** - lightweight, meta-materials for tailored EM properties, ultrahigh dielectric for micro-antennas, wavelength conversion

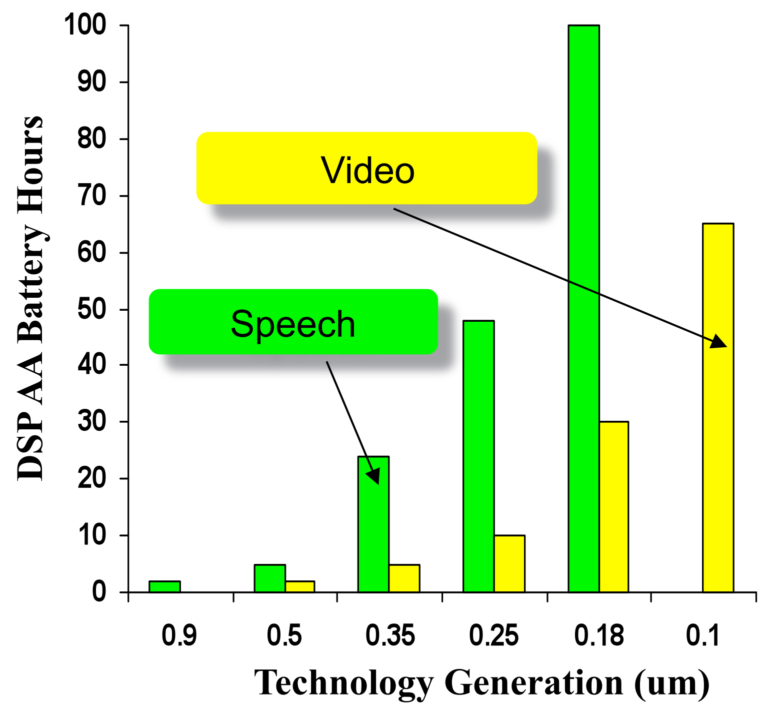
- **Data Storage** - nanostructured magnetics, tailored magnetoresistive materials

- **Displays** - lighter weight, paperlike, low power


**Major trend:**
**Drive down cost, size and power consumption of components for systems**

# VLSI Scaling: Moore's Law - a law of economics

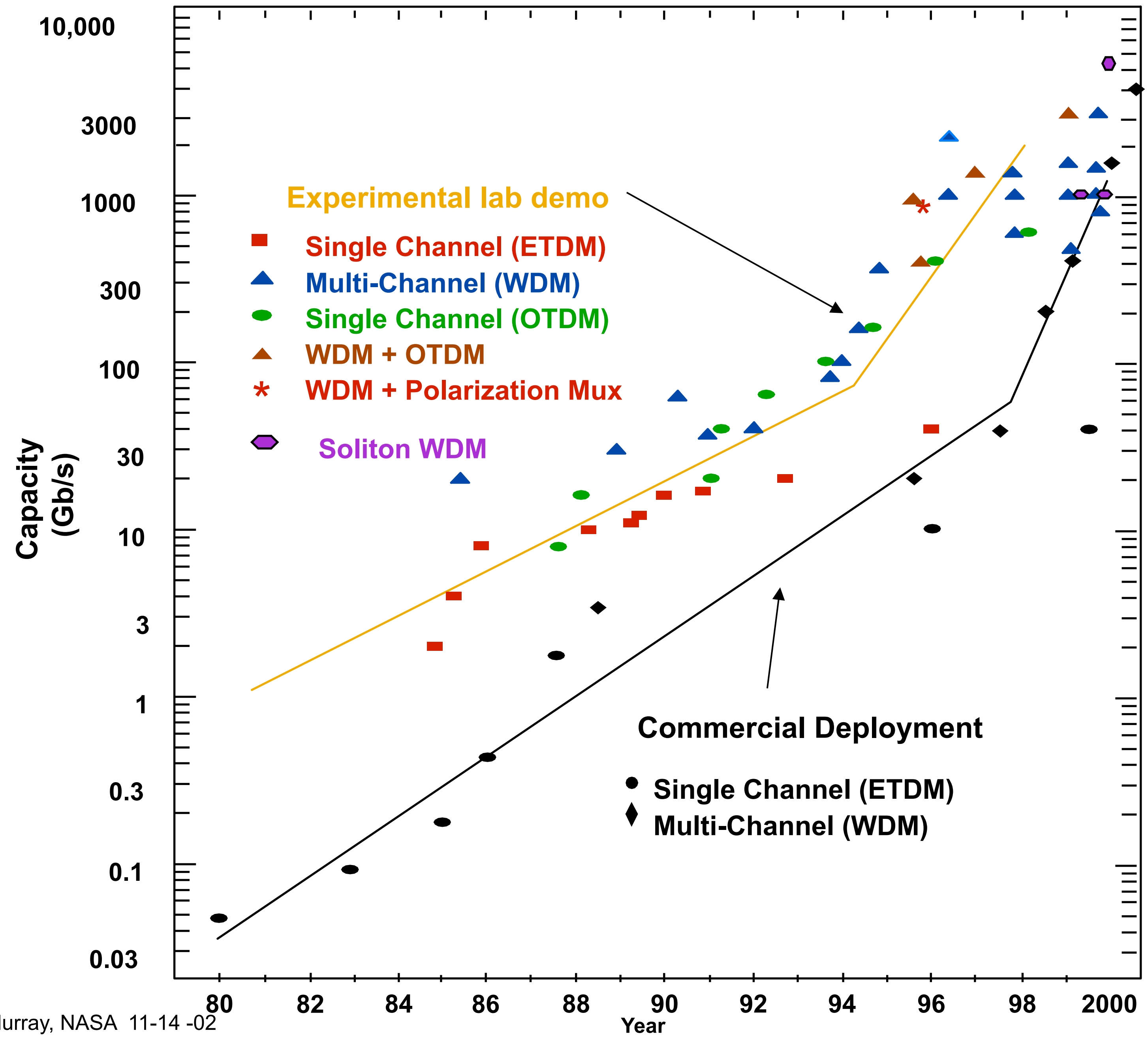



- ⇨ Decrease transistor dimensions by k, drop voltage by k
- ⇨ Circuit area reduced to $1/k^2$, speed increased by k
- ⇨ Power per circuit reduced to $1/k^2$, power per area constant
- ⇨ Cost reduced by area ~ $1/k^2$

C. A. Murray, NASA 11-14 -02

# The " Moore curve" for transmission capacity of lightwave systems




ARC-11-18-99

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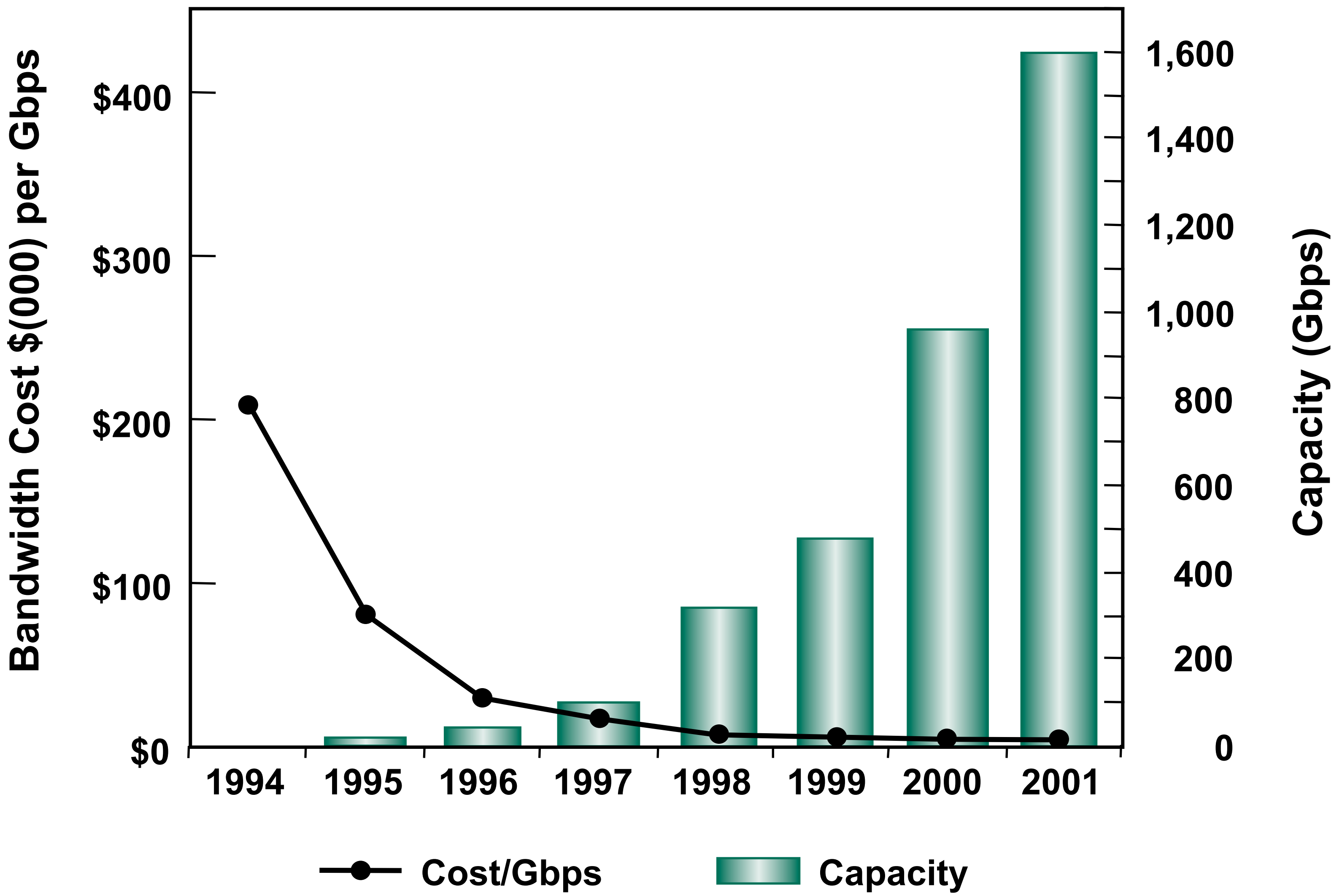
Capacity and cost of optical transport improves by approximately a factor of 2 each year - steeper technology curve than silicon electronics!

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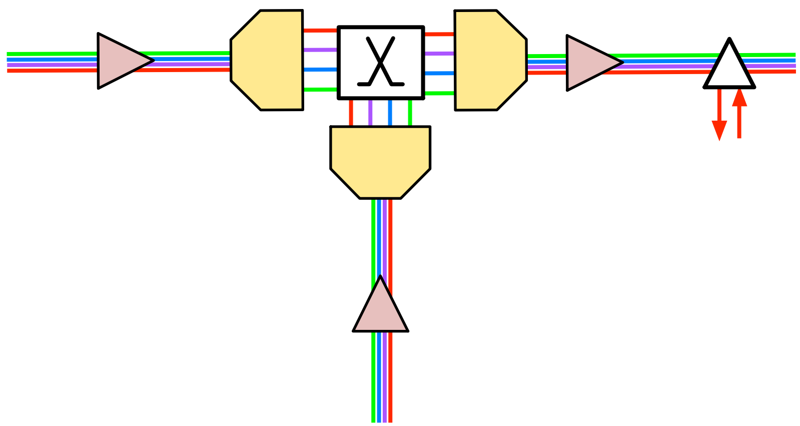
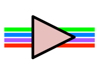
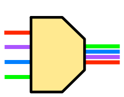
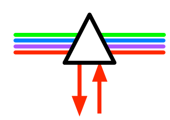
# For terabit-rate systems, all-optical network elements are needed

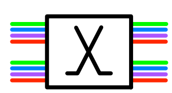


- Today WDM ( wavelength division multiplexing) is used for point-to-point links
- Cross-connect and add/drop functions are performed electronically
- Converting signal from optical to electronic, performing the switching function, and converting back to optical ( OEO ) is very expensive

 **Fiber Amplifier**

 **Wavelength Multiplexer/Demultiplexer**

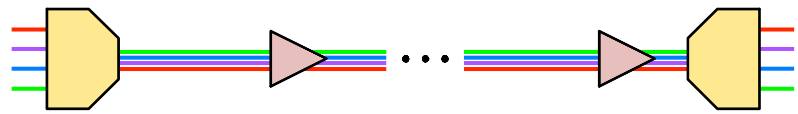
 **Electronic Add/Drop**

 **Electronic Cross-Connect**

# Optical Transport ⇒ Optical Networks:
## Evolution to all-optical elements
## Route and manage optical wavelength channels

### WDM/Point-to-Point Transport

- High Capacity Transmission



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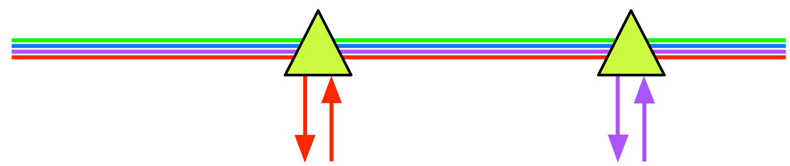
### Fixed WDM/Multipoint Network

- Fixed Sharing Between Multiple Nodes
- Passive Access of Wavelength Channels



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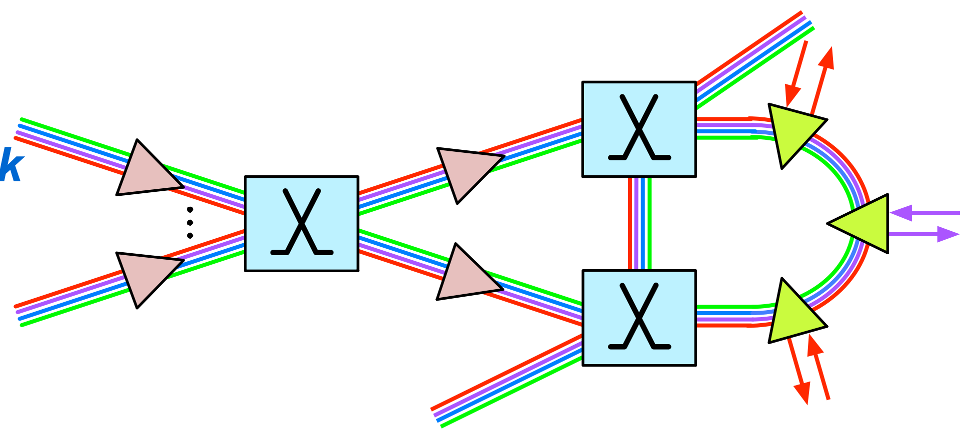
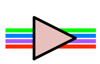
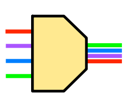
### Optical XC and Optical Add/Drop Reconfigureable WDM/Multipoint Network

- Automated Connection Provisioning
- Flexible Adjustment of Bandwidth
- Network Self-Healing/Restoration
- Scalable, Cost Effective Networking

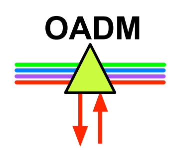




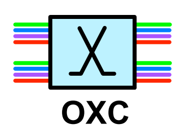
Fiber Amplifier



Wavelength Multiplexer/Demultiplexer




Wavelength Add/Drop




Wavelength Cross-Connect

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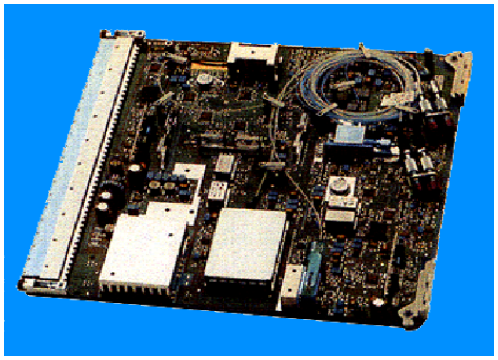
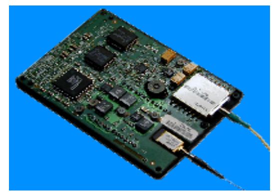
# Trend 1: Optoelectronics Integration lowers cost of optoelectronic end terminals (OEO's)





**1997**

Discrete board

**1999**

Subsystem in a package

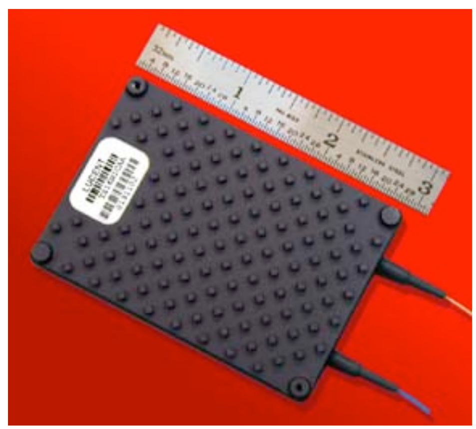
**2000**

OE-IC Multi-Chip Module

2.5 Gb/s & 10 Gb/s; 16:1Mux
- Short reach & long haul versions

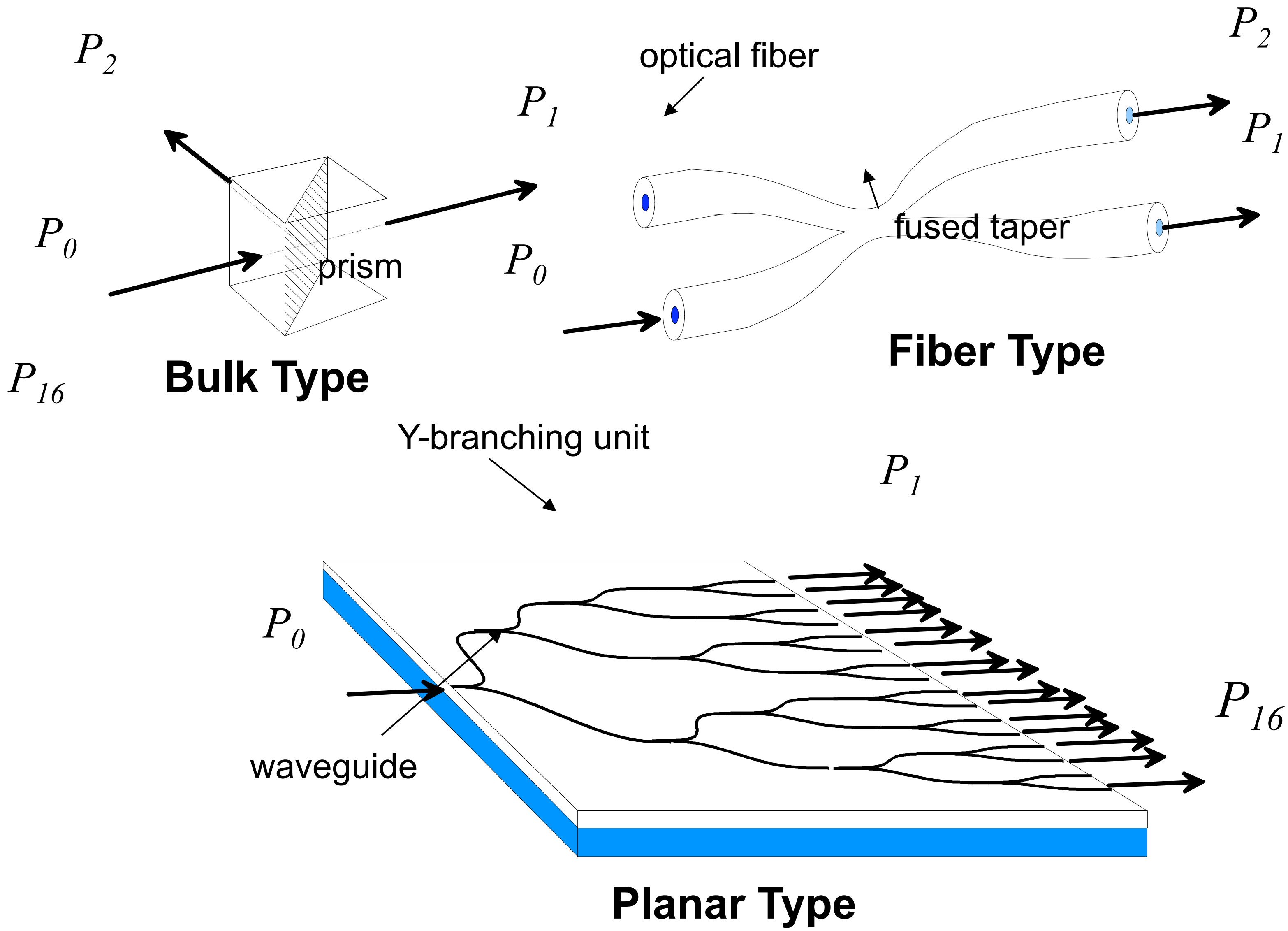
SONET/SDH, ATM, POS and SDL terminations

U3/U3+ data interface

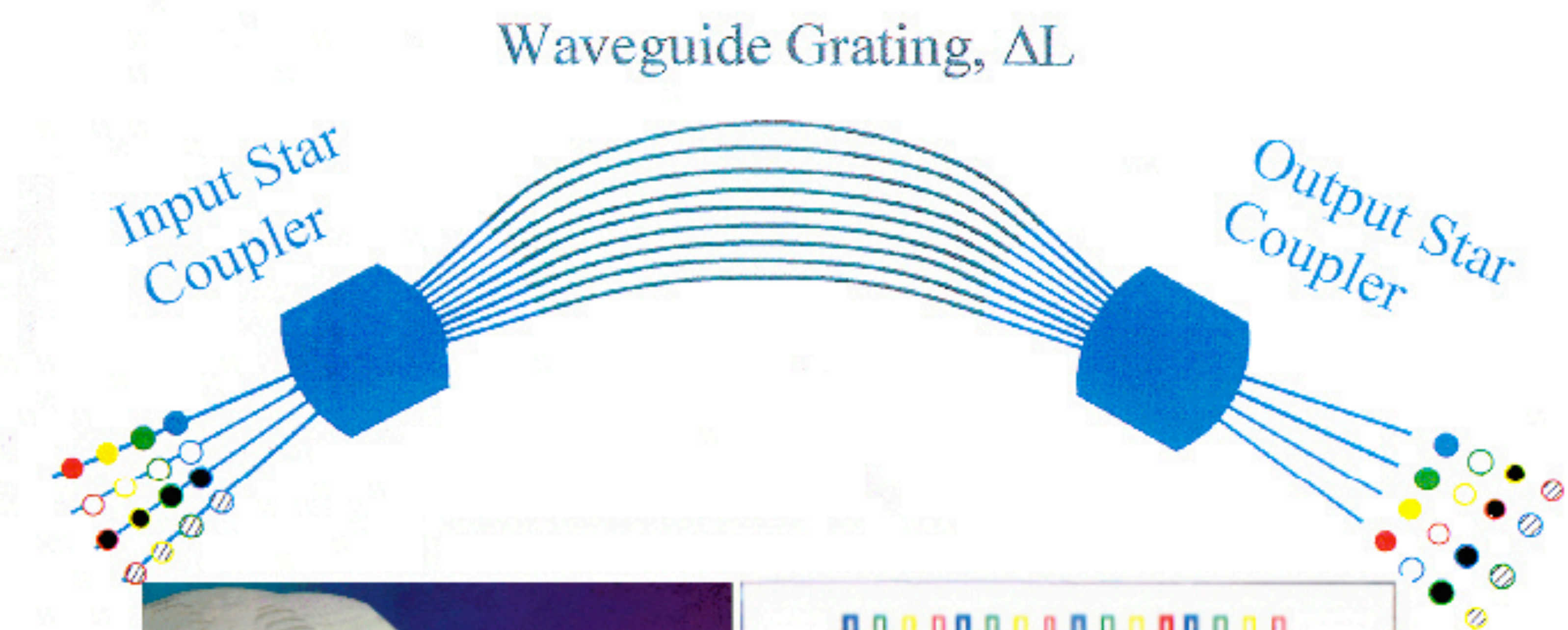


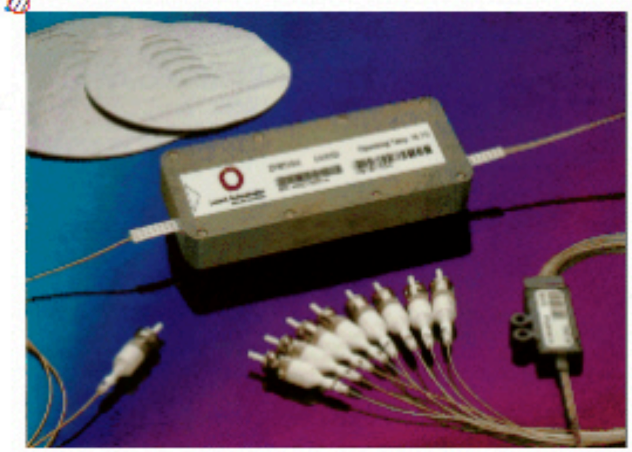
- Size Reduction (>10X)
- Power Reduction (>3X)
- Cost Reduction through Advanced Packaging & Assembly (> 3X)

# Trend 2: All Optical Circuits
# Some configurations



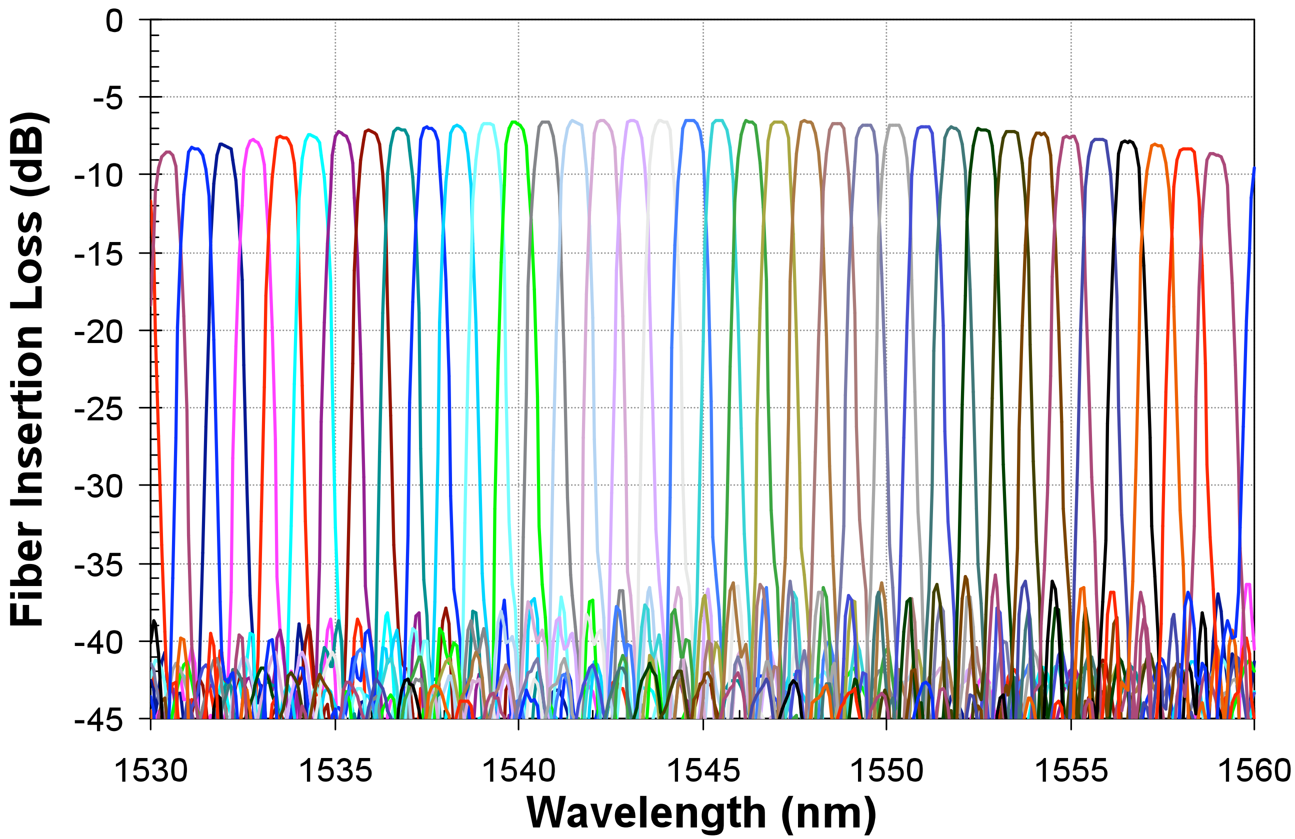
# Silica Waveguide Grating Router

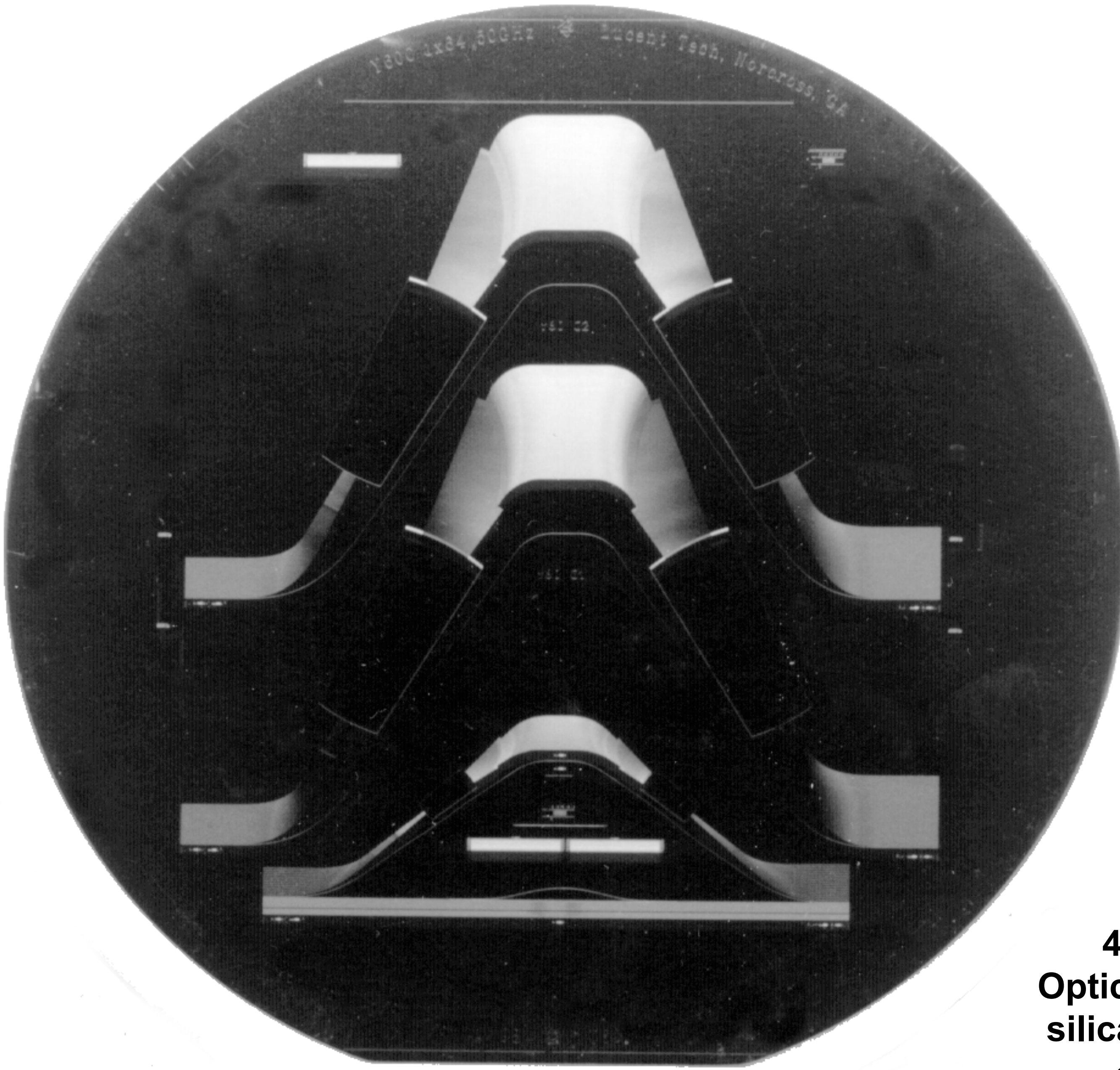



comb filtering adds
N wavelength outputs per fiber
over N spectral periods

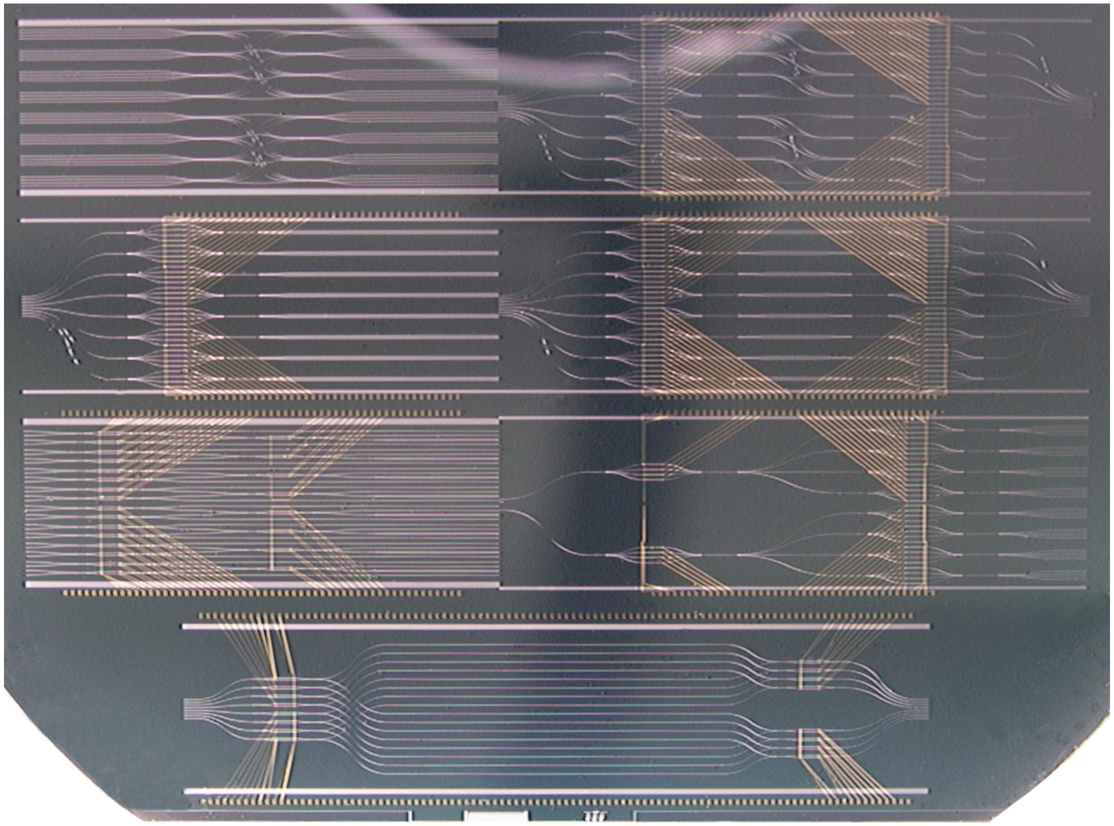
# 40-Port Waveguide Grating Router





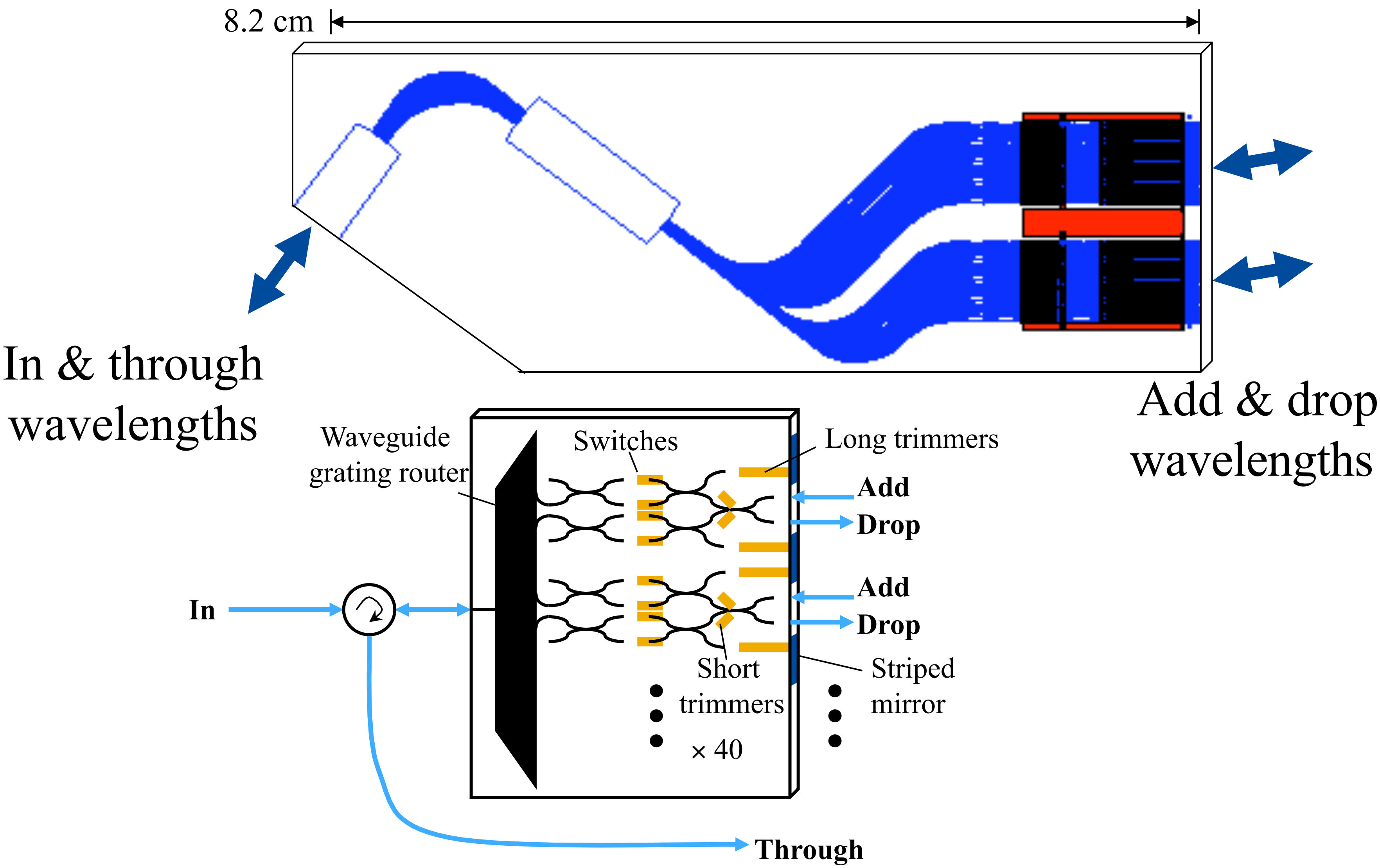

**40 Channel Optical Multiplexer silica waveguides on silicon**

# Thermo-Optic Mach Zender Switches



**1x4, 1x16, 4x4, 8x8, dilated 2x2**

# Compact Optical Add/Drop can be built monolithically with waveguides and thermo-optic MZ switches

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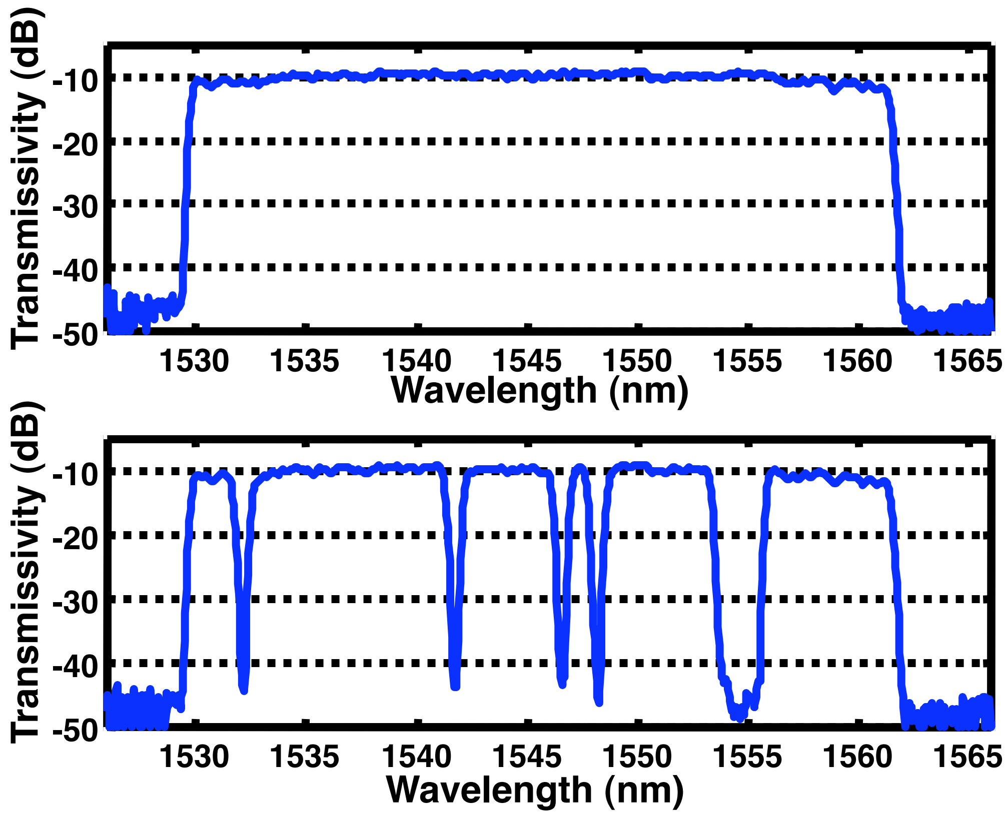
## When all channels are THRU, the input spectrum is exactly reconstructed at the output

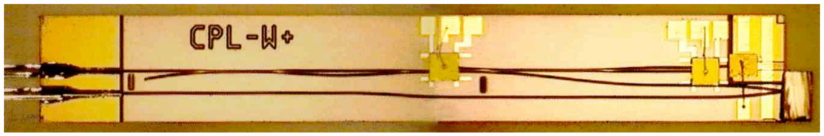
All through

Dropping of chs. 8, 9, 10, 17, 19, 25, & 37

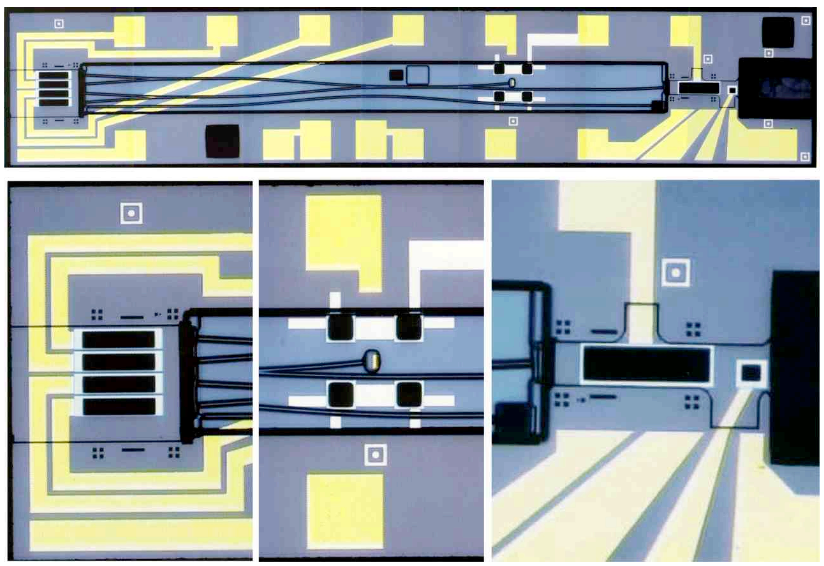



***Doerr et al., OFC 2000***

# Further optoelectronic integration:



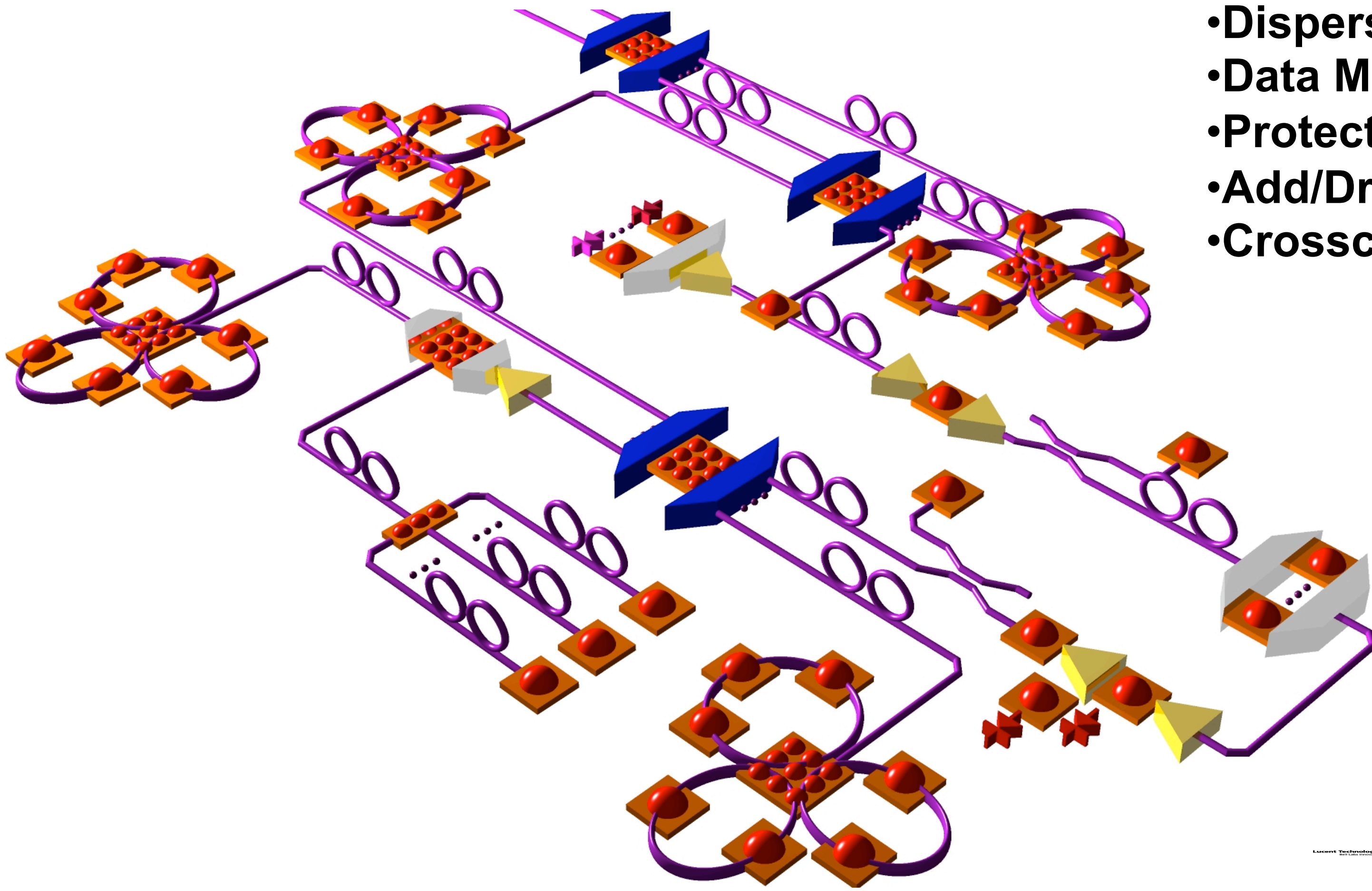

**Integrated Optical Transmitter on silicon**



**Integrated Wave Length Selectable Laser on silicon**

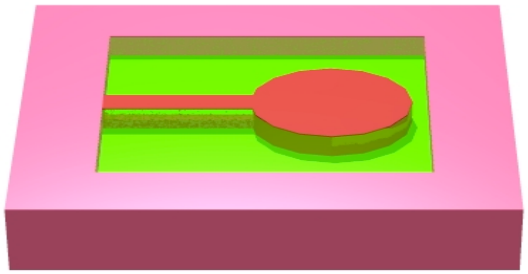
# Micromachines in Optical Networks

- •Variable Attenuators
- •Spectral Equalizers
- •OLS Monitors
- •Dispersion Compensators
- •Data Modulators
- •Protection Switches
- •Add/Drop Multiplexers
- •Crossconnects

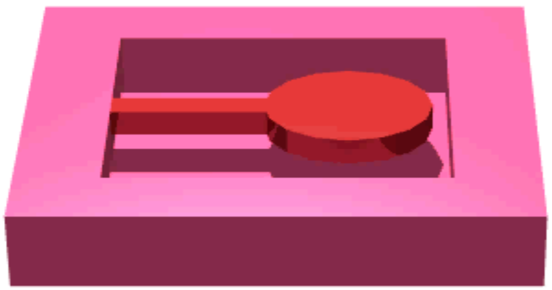


# Making Micromachines

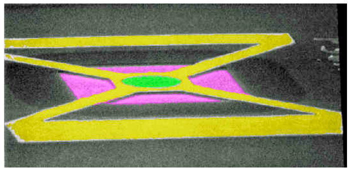
Patterned layers of silicon, oxides and metals are deposited epitaxially.



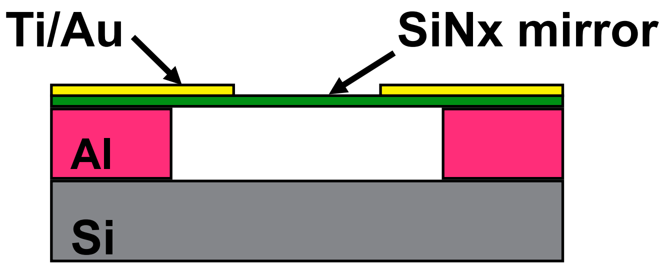
The oxide is removed using HF, releasing the moving parts.

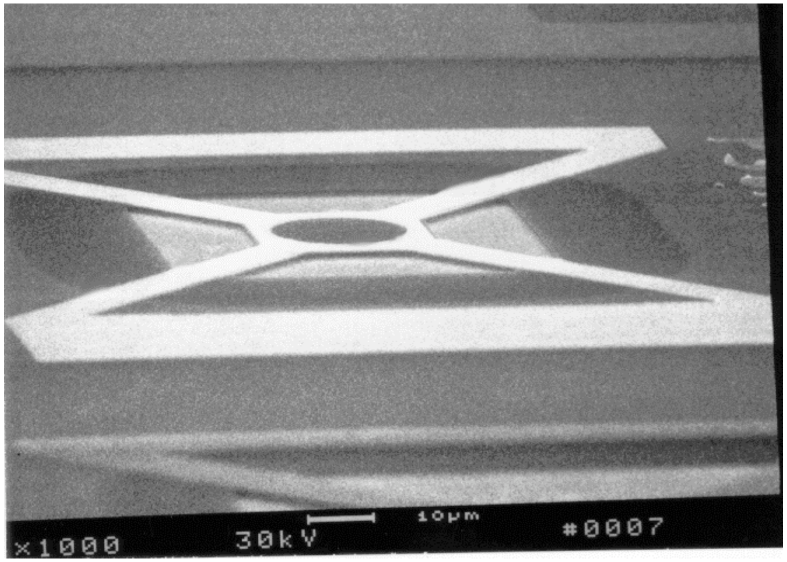


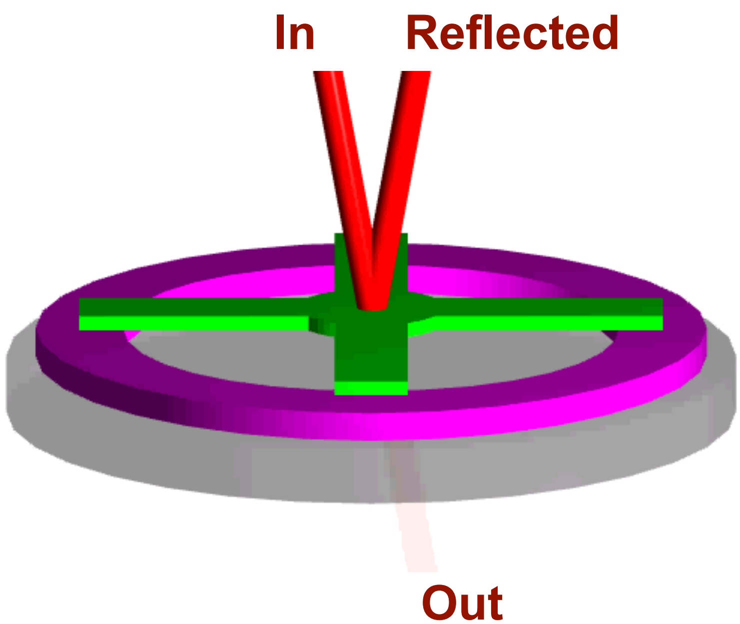
Some micromachines self-assemble during release.

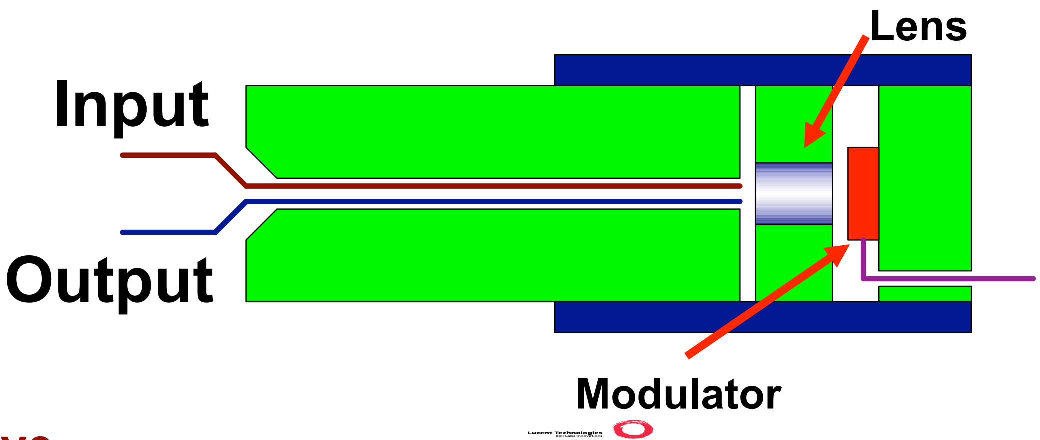


# Variable Attenuator/Modulator




- •No voltage (undeflected): reflective
- •Voltage (deflected): transmissive

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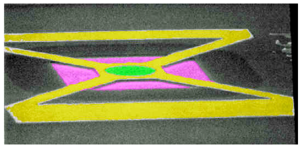
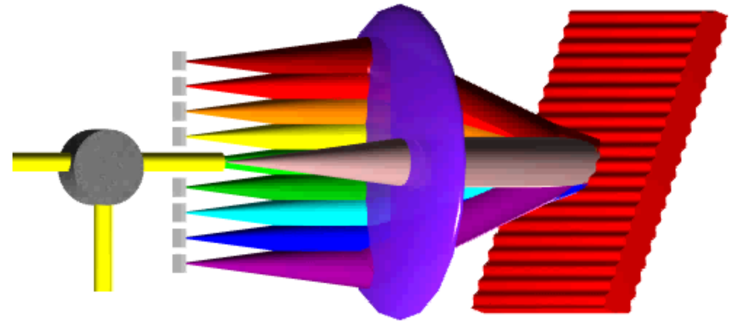
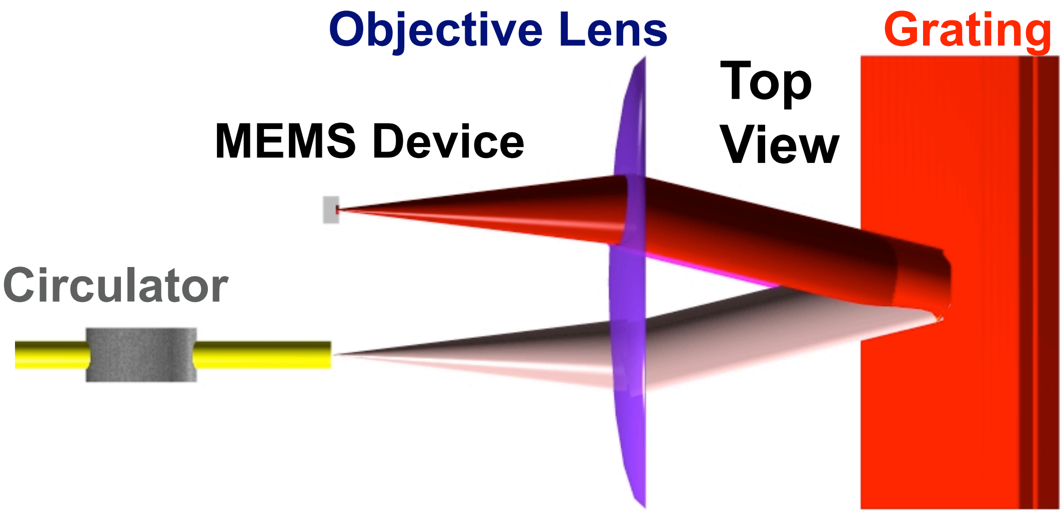
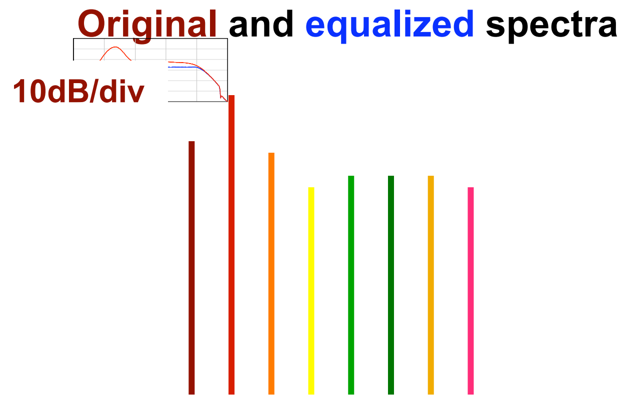
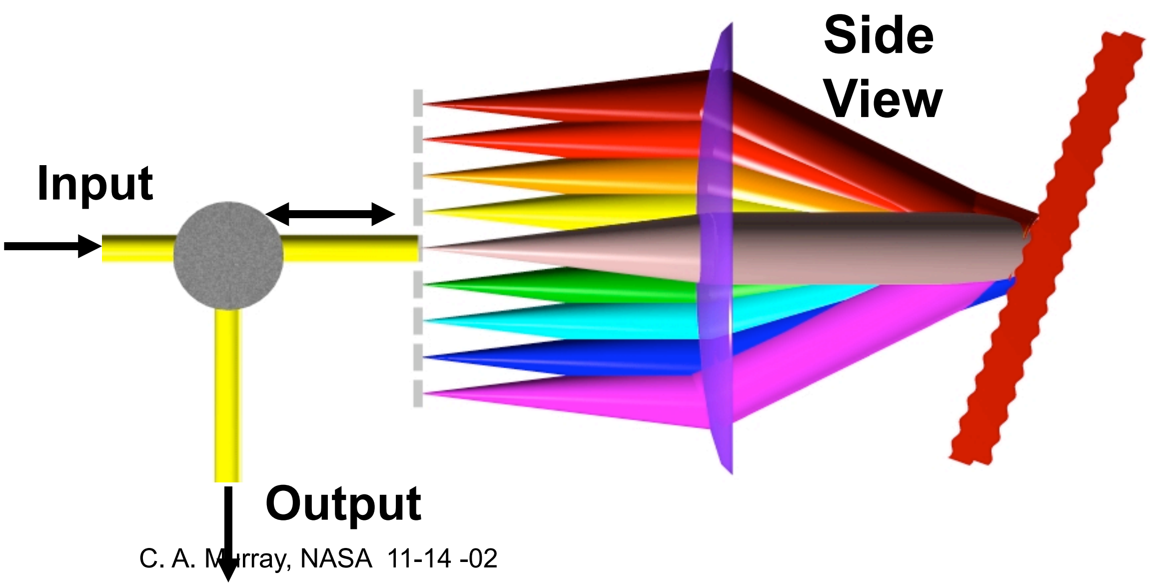


# MEMS Spectral Equalizer

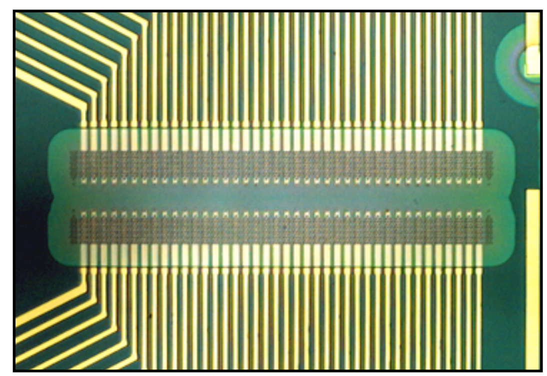





MEMS deformable mirror

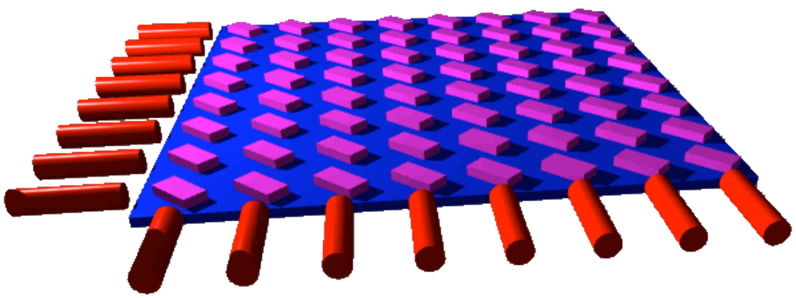


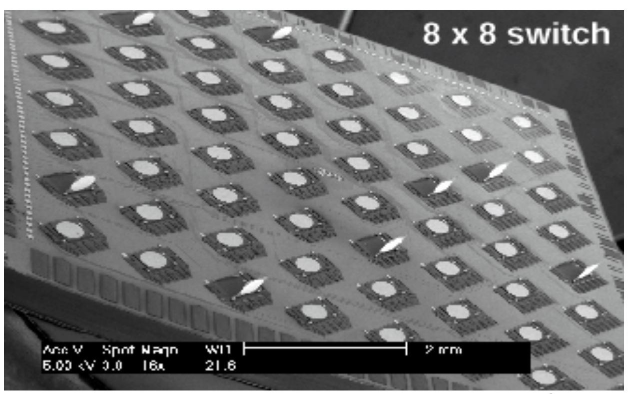
# Two Versions of Optical Crossconnects

Lucent Technologies
Bell Labs Innovations

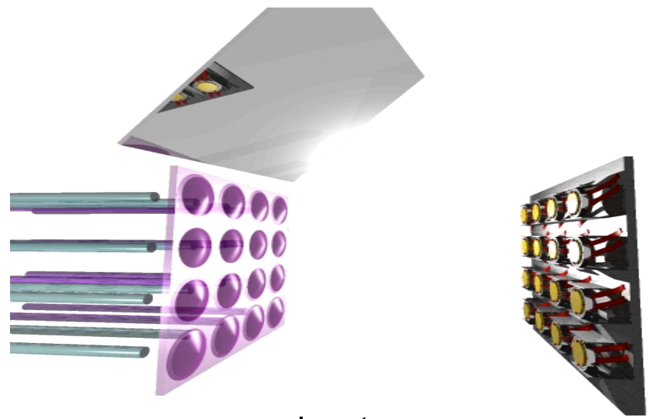
- Planar
- Digital control
- $N^2$ Components
- Compact and easy for small N

- 3D Beam Steering
- Analog Control
- 2N Components
- Scalable to large size

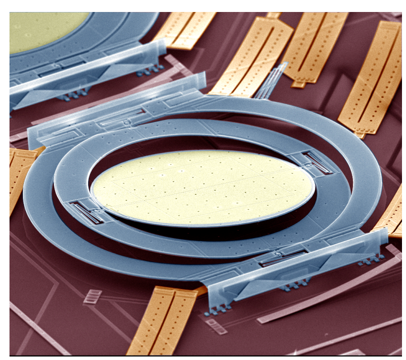


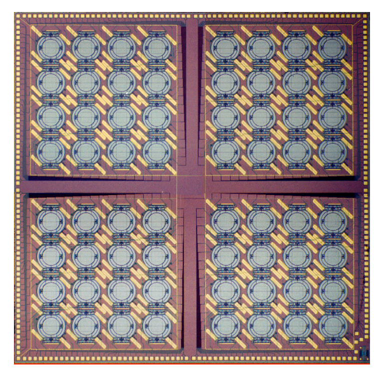



AT&T

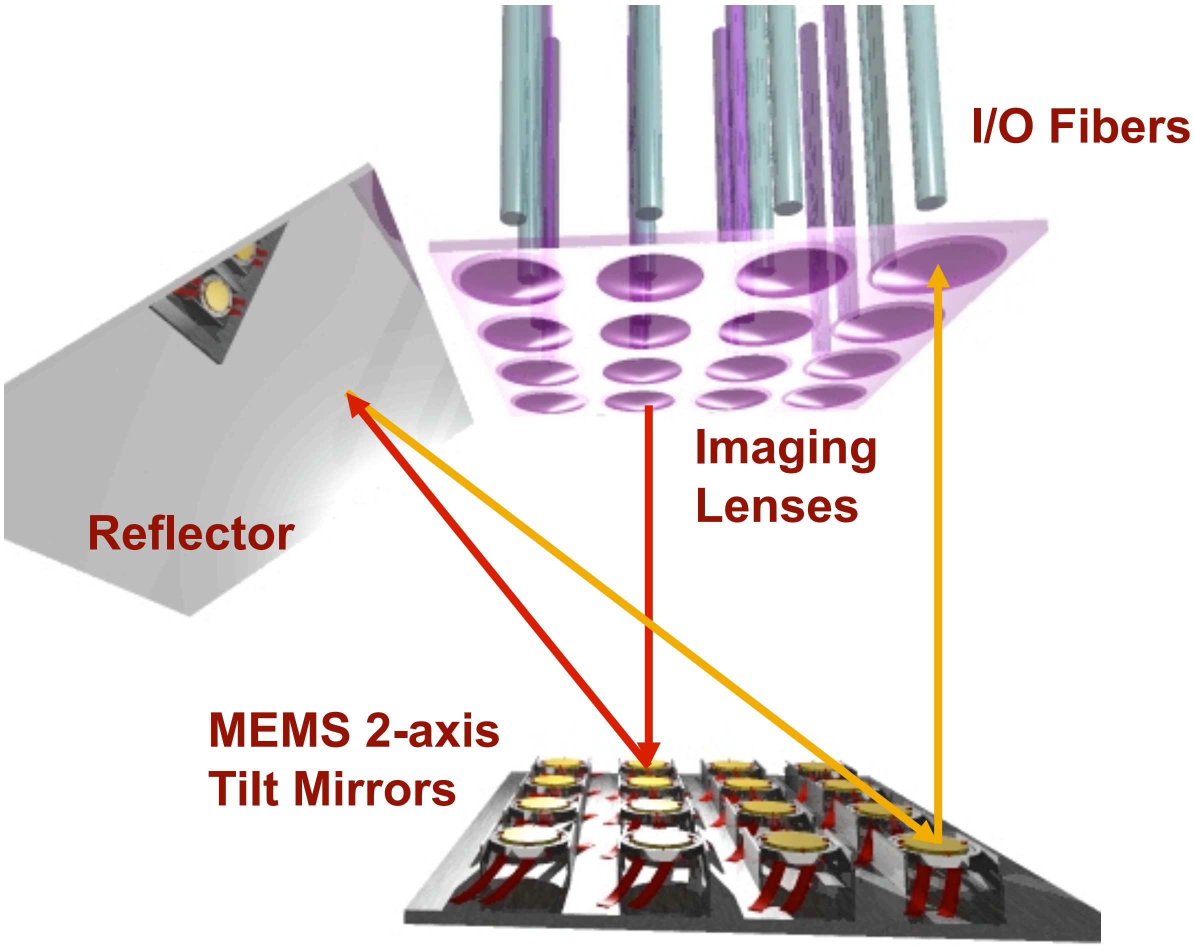


Lucent

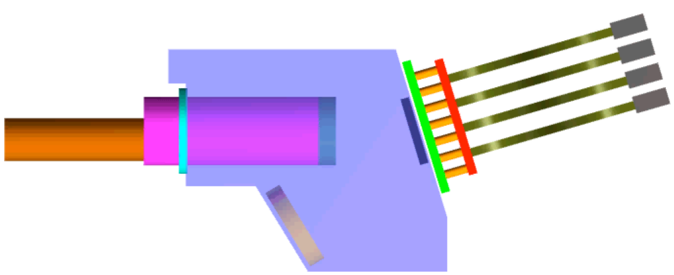


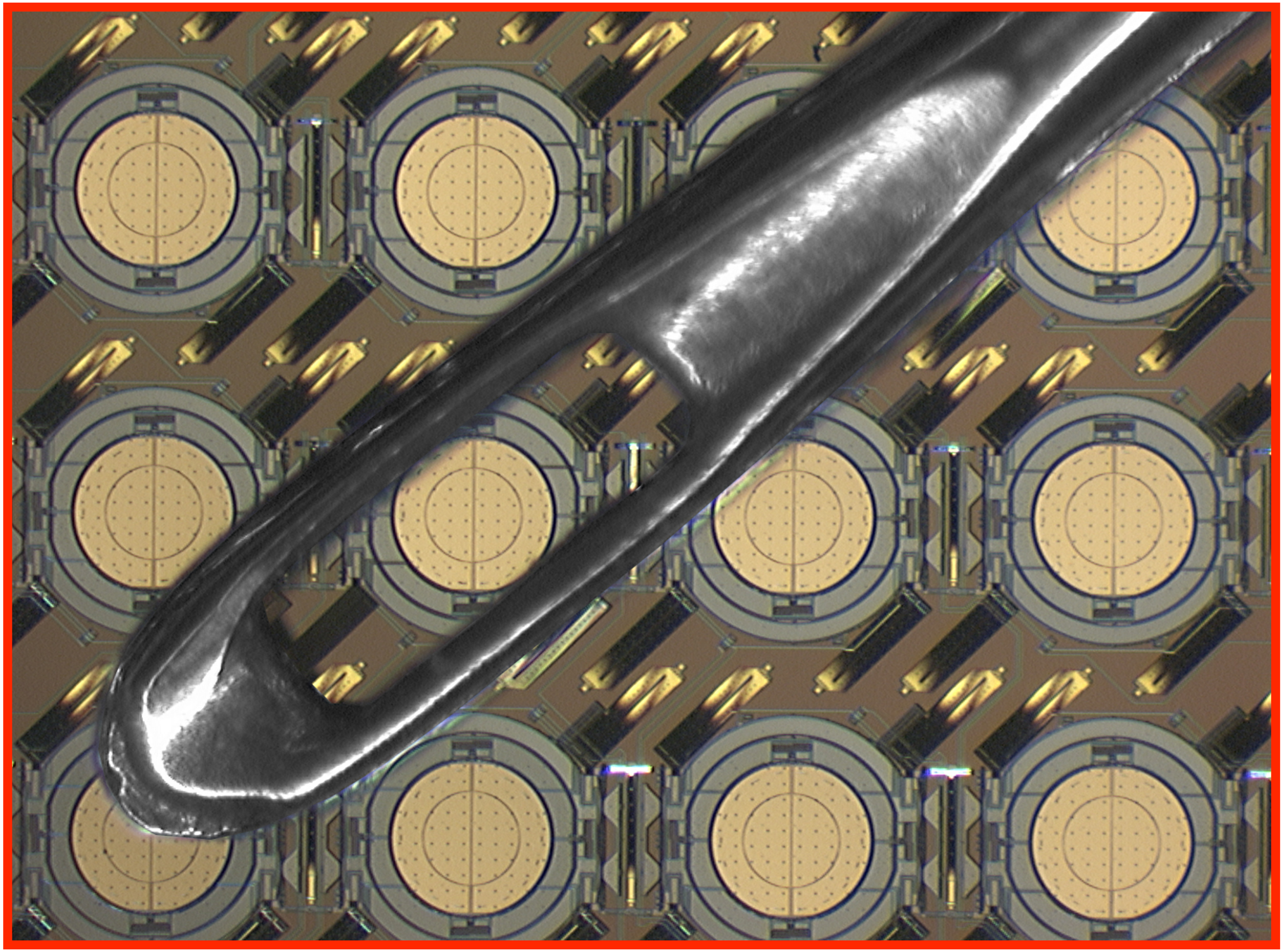


# Micromechanical Optical Crossconnect




256-mirror array





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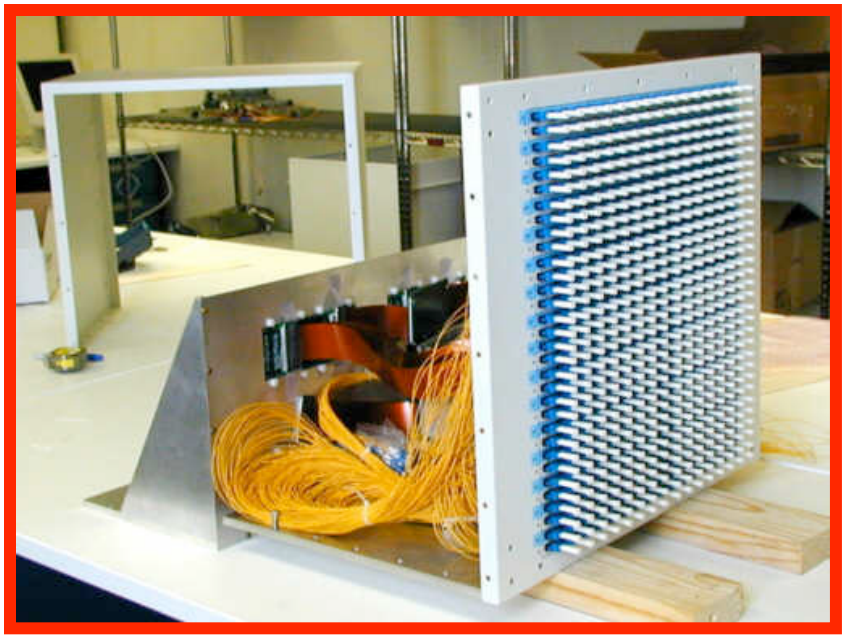
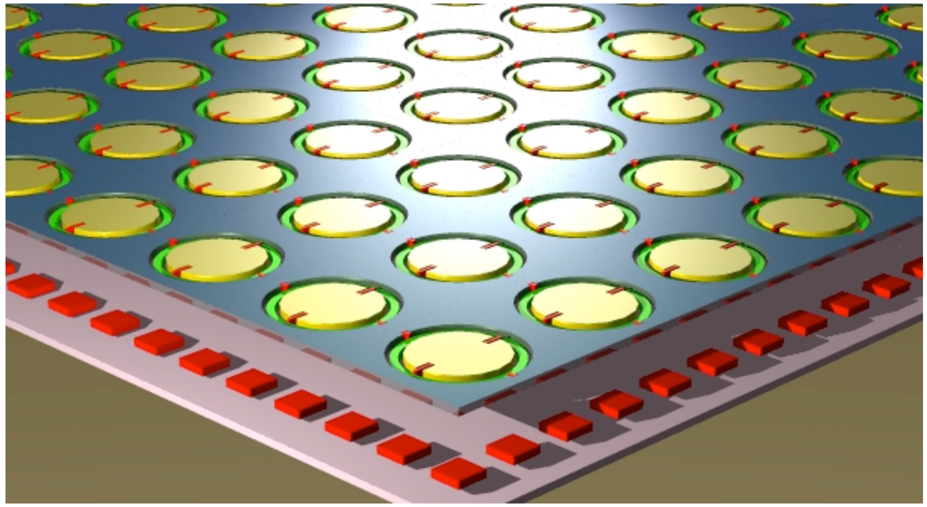
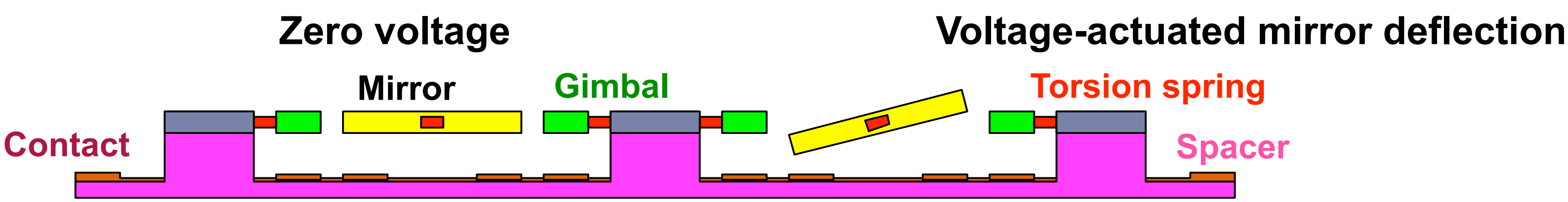
# 256x256 MEMS Optical Cross-connect Subsystem

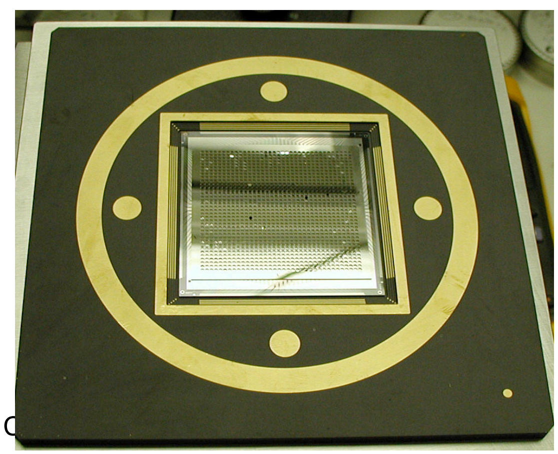


The WaveStar LambdaRouter Ready For Shipment - 7/30/2000

# Single-Crystal Silicon Micromirror Array

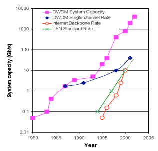




•1296 mirror array

# DWDM Capacity and Interface Speeds – Trend 3: x4 faster data speed eventually is ~x2.5 in cost compared to 4 separate OEO terminal line cards at the original speed

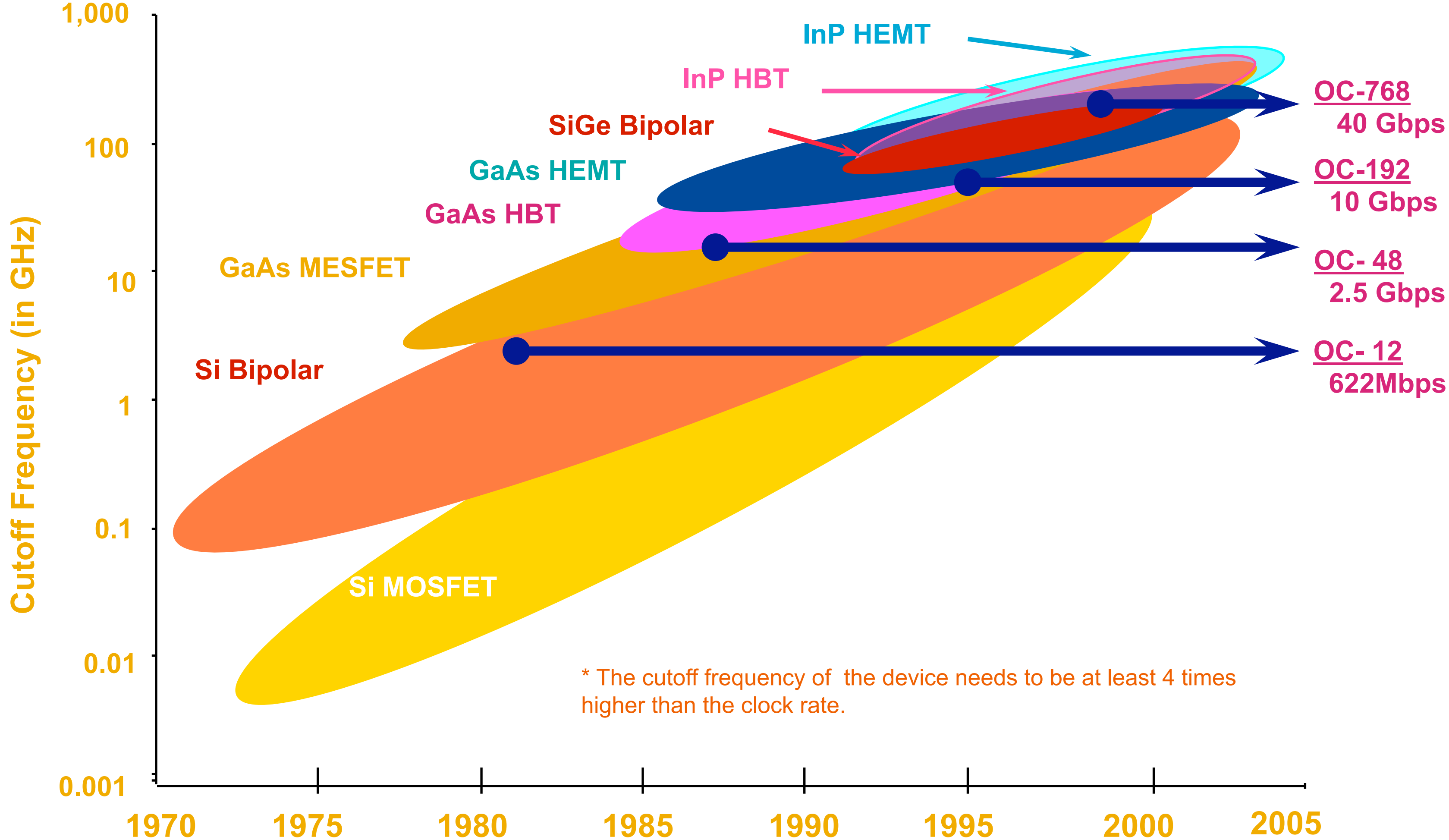



Single-fiber capacity doubles every year

I/O rate from routers and ATM switches passes 10Gb/s in 2000

40Gb/s wavelengths needed to support data terminal interfaces by 2003

# *Technology Roadmap for Lightwave Electronics*

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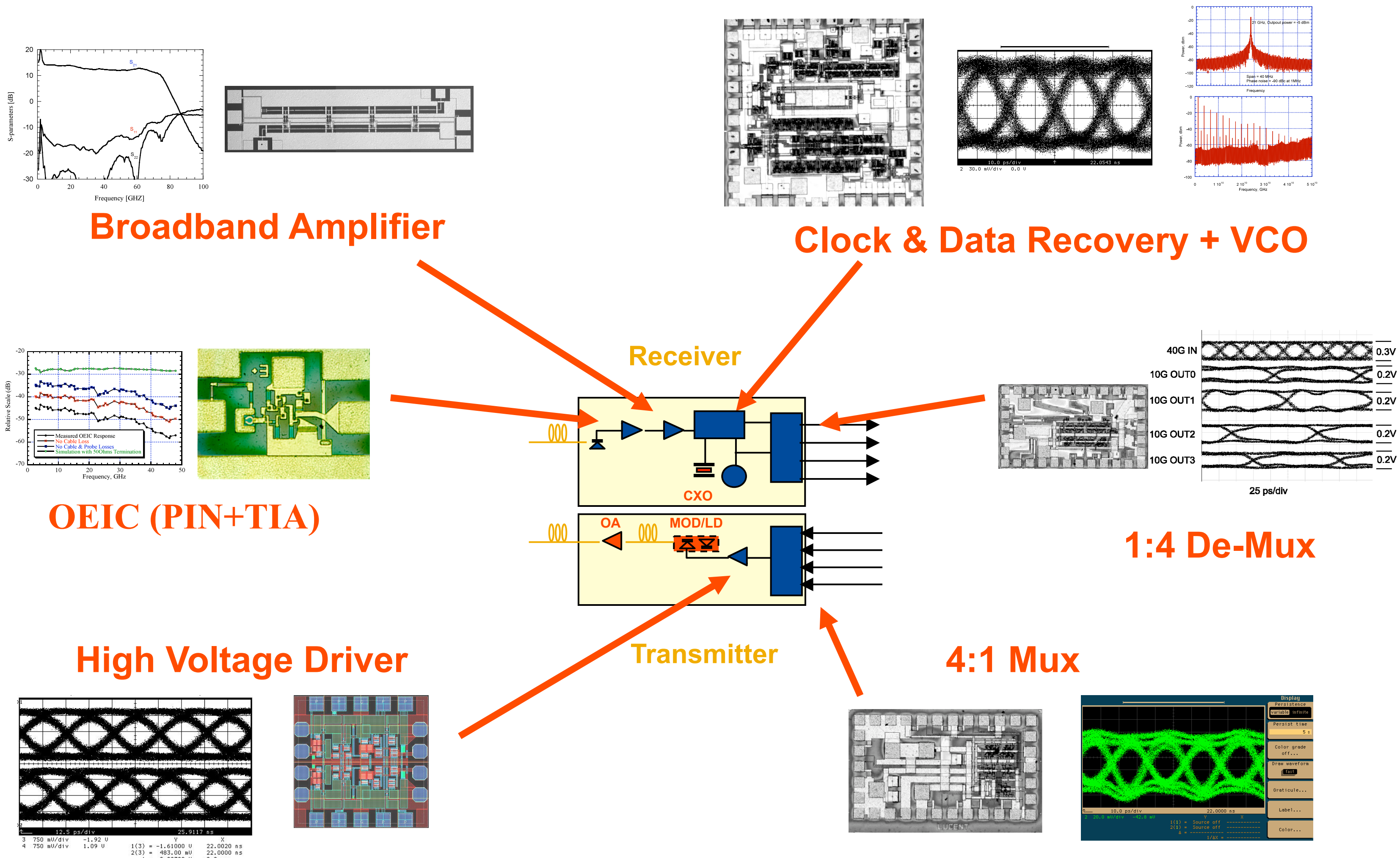
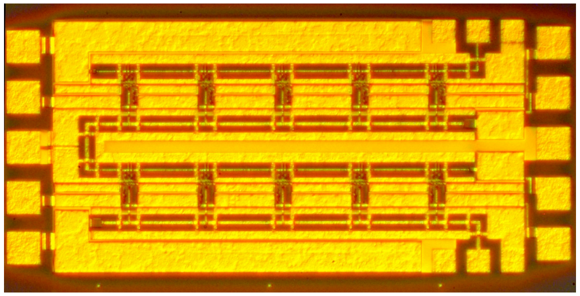
# InP Electronics for 40 Gbps Lightwave Transceiver

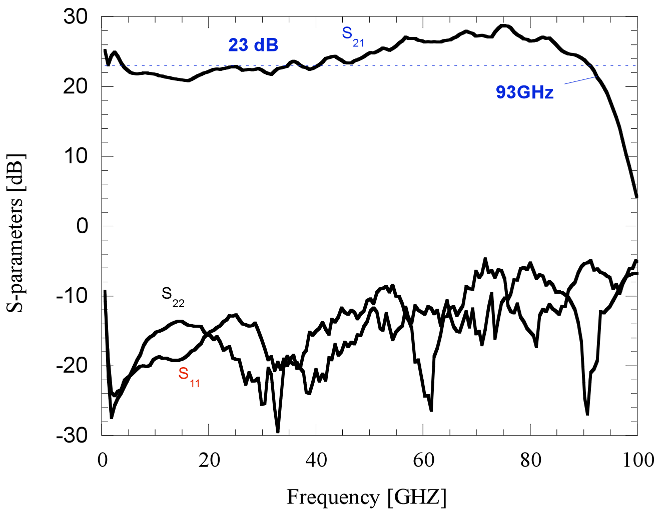


# Toward 100 + Gbps Data Rate

***Fastest bipolar amplifier***

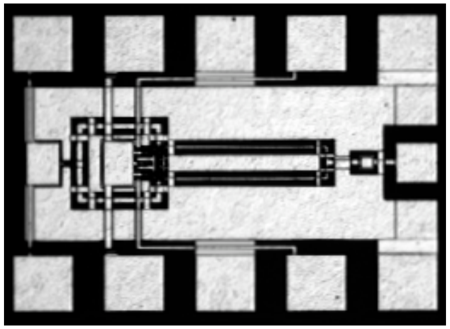
- **3-dB bandwidth: 93 GHz**
- **Gain-bandwidth: 1.3 THz**

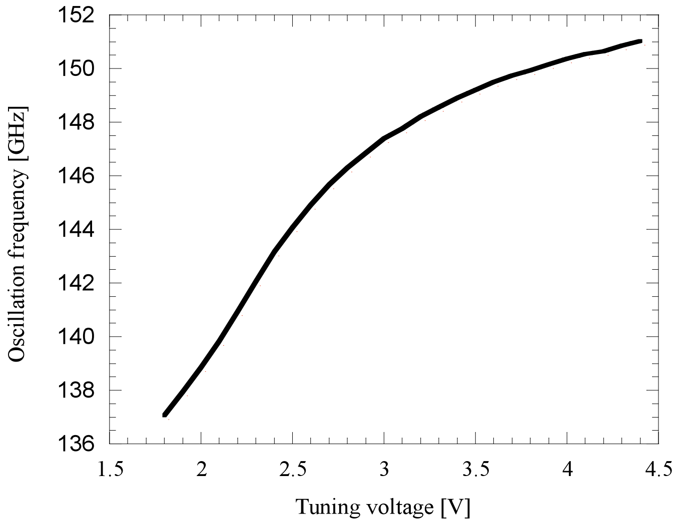




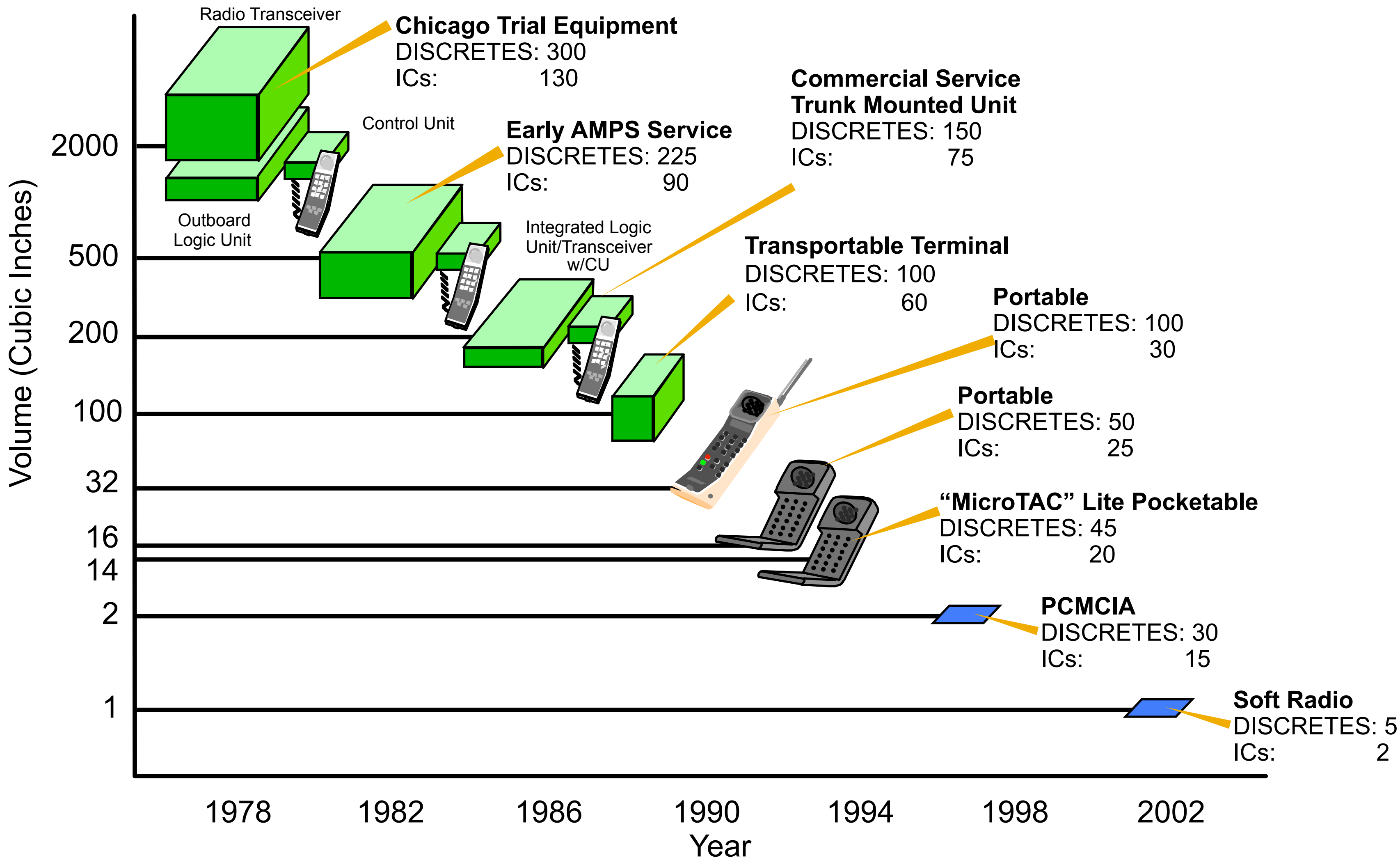

***Fastest bipolar oscillator***

- **highest frequency: 150 GHz**
- **broadest tuning: 14 GHz**





# Wireless handset evolution

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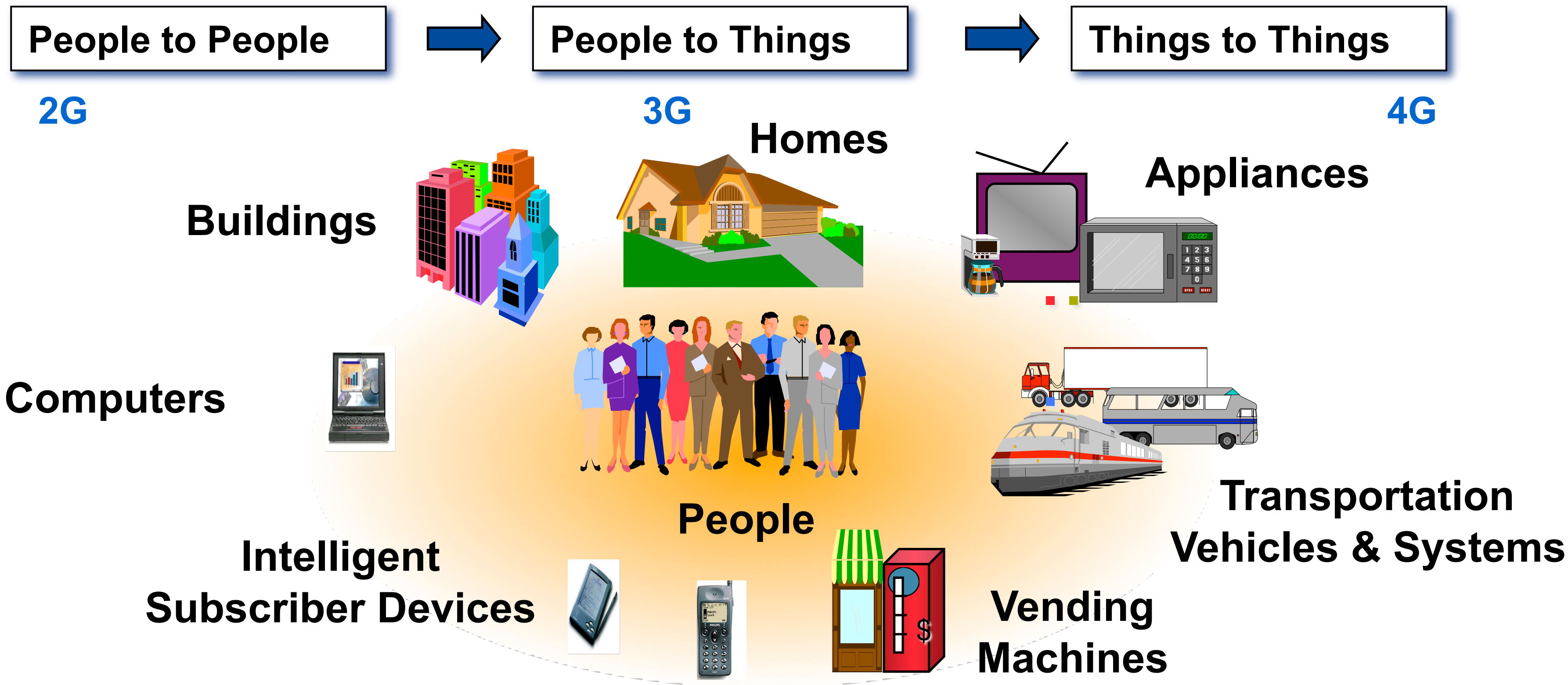
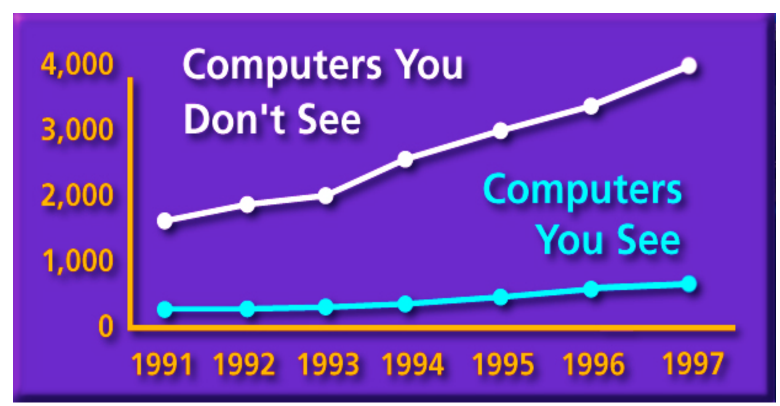
# Wireless Communications Network Transformation




- ➡ **Multiple Connections per Person**
- ➡ **Nearly All Household and Business Devices**
- ➡ **Full Time Connectivity:**
  - ■ **Broadband: Entertainment & High End Applications**
  - ■ **Wireless: Convenience & Portability**
  - ■ **interchatter between things will surpass messaging between people by 2010**

**<u>You only notice the network when its NOT there</u>**

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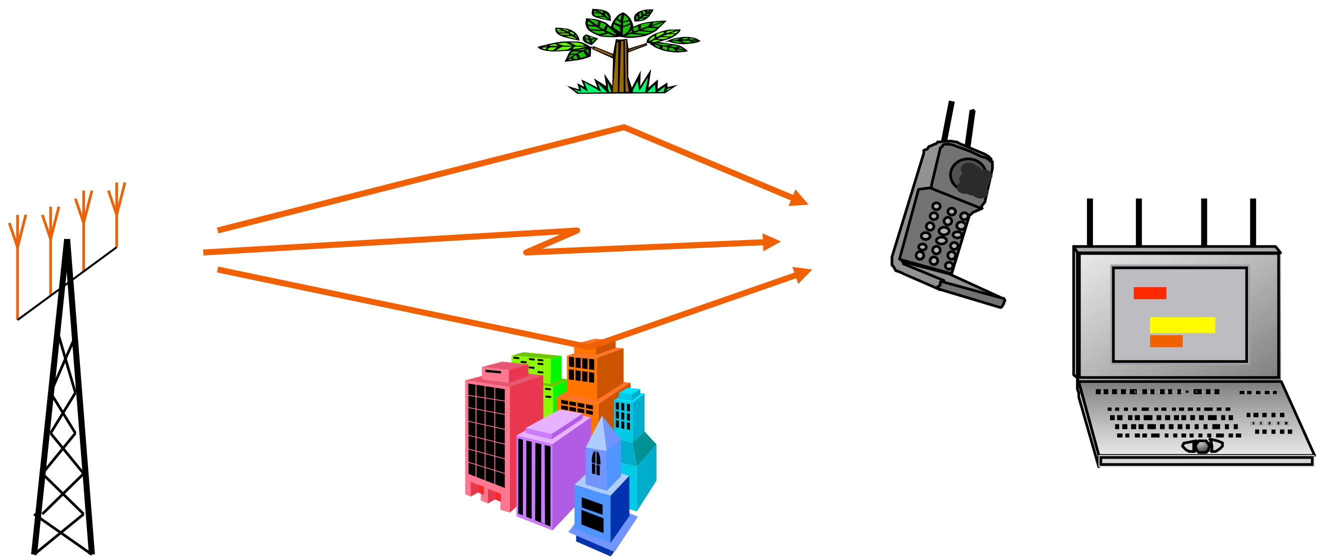
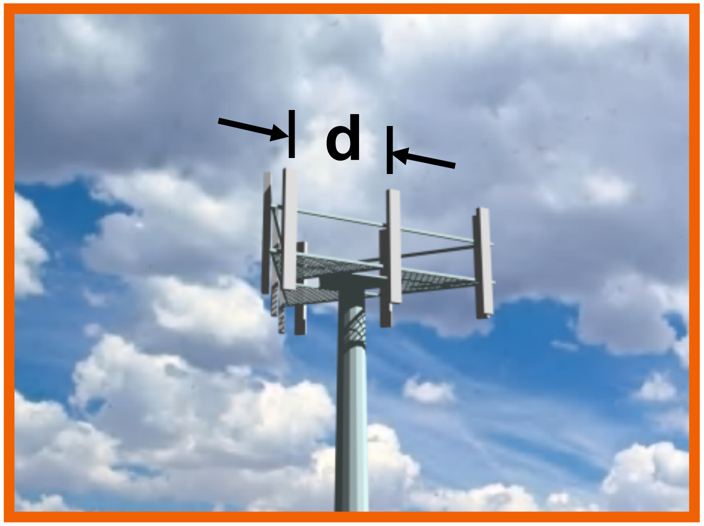
# The wireless channel



- Multipath propagation has historically been regarded as an impairment because it causes signal fading.

- **Recent advances in information theory have shown that with multiple antennas at both the transmitter and receiver, multipath propagation can substantially increase the data rate.**

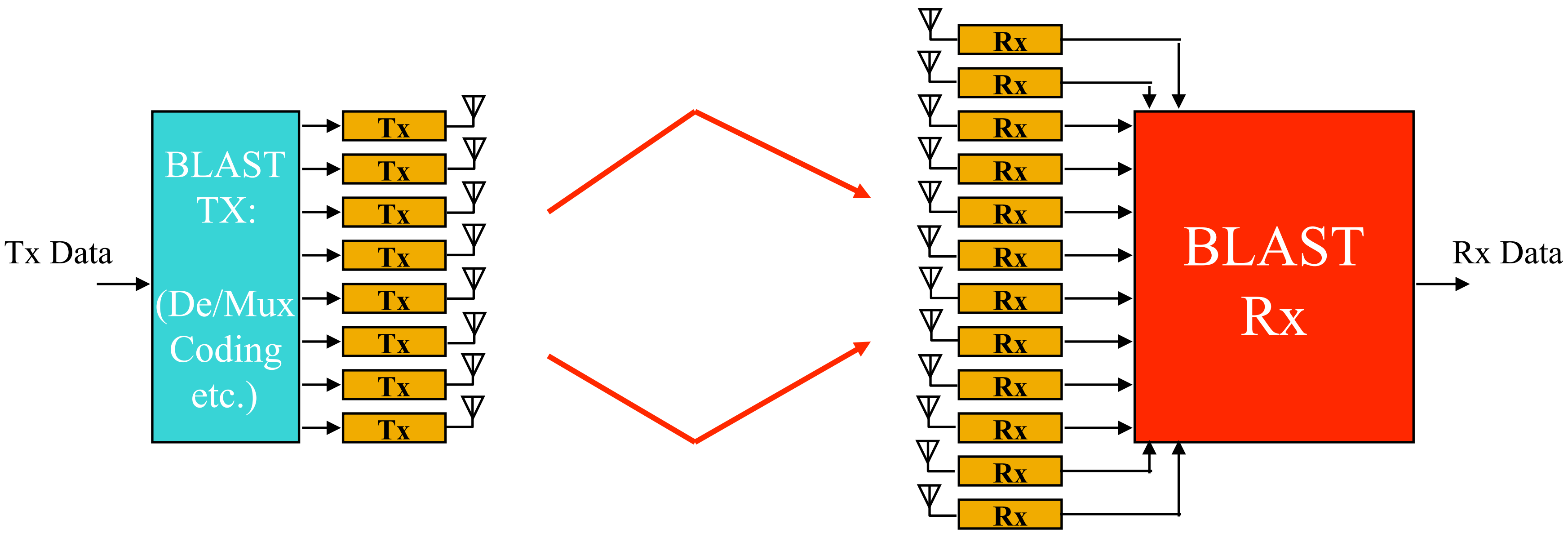
# Multiple In  Multiple Out  Antenna configurations




**Increasing capacity**

| | | |
|---|---|---|
| **<u>d > wavelength</u>** **(diversity)** | **Tx diversity** | **BLAST** |
| **<u>d < wavelength</u>** **(phased array)** | **switched beams** | **steered beams** |

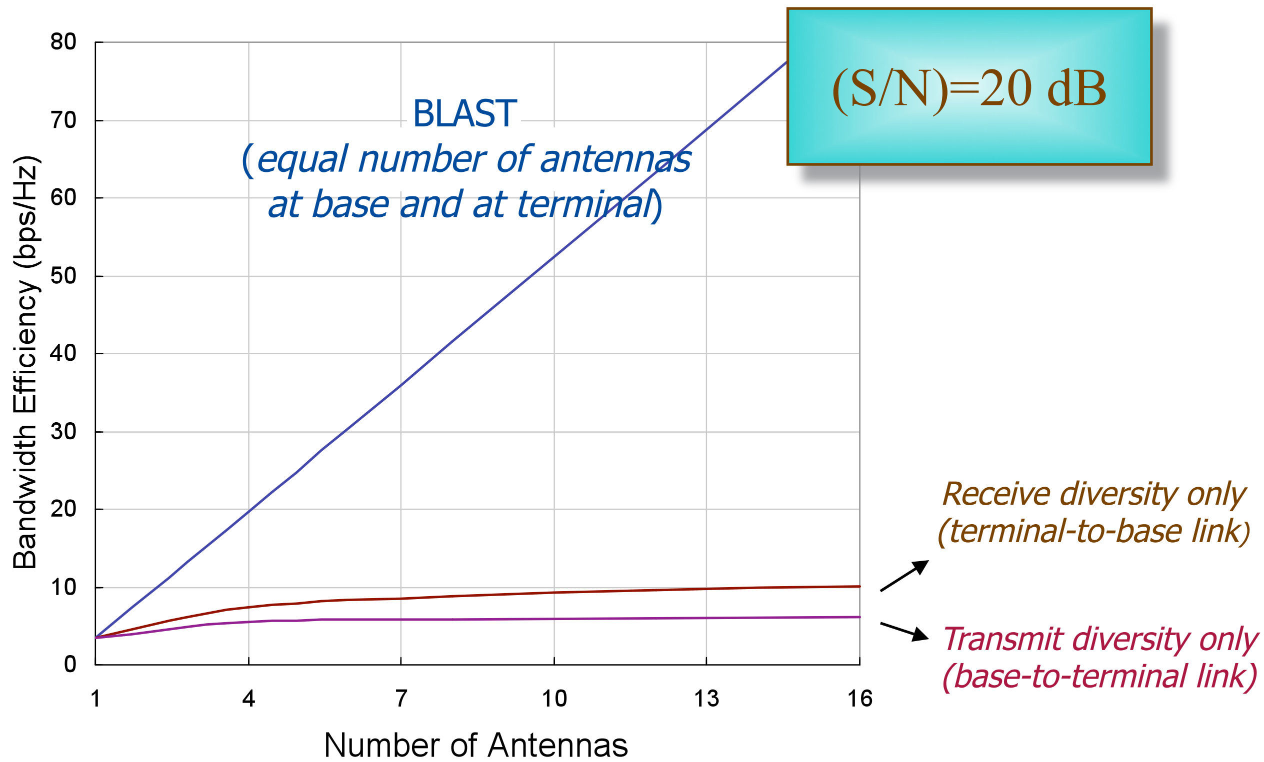
# BellLabsLAyeredSpaceTime transceiver architecture



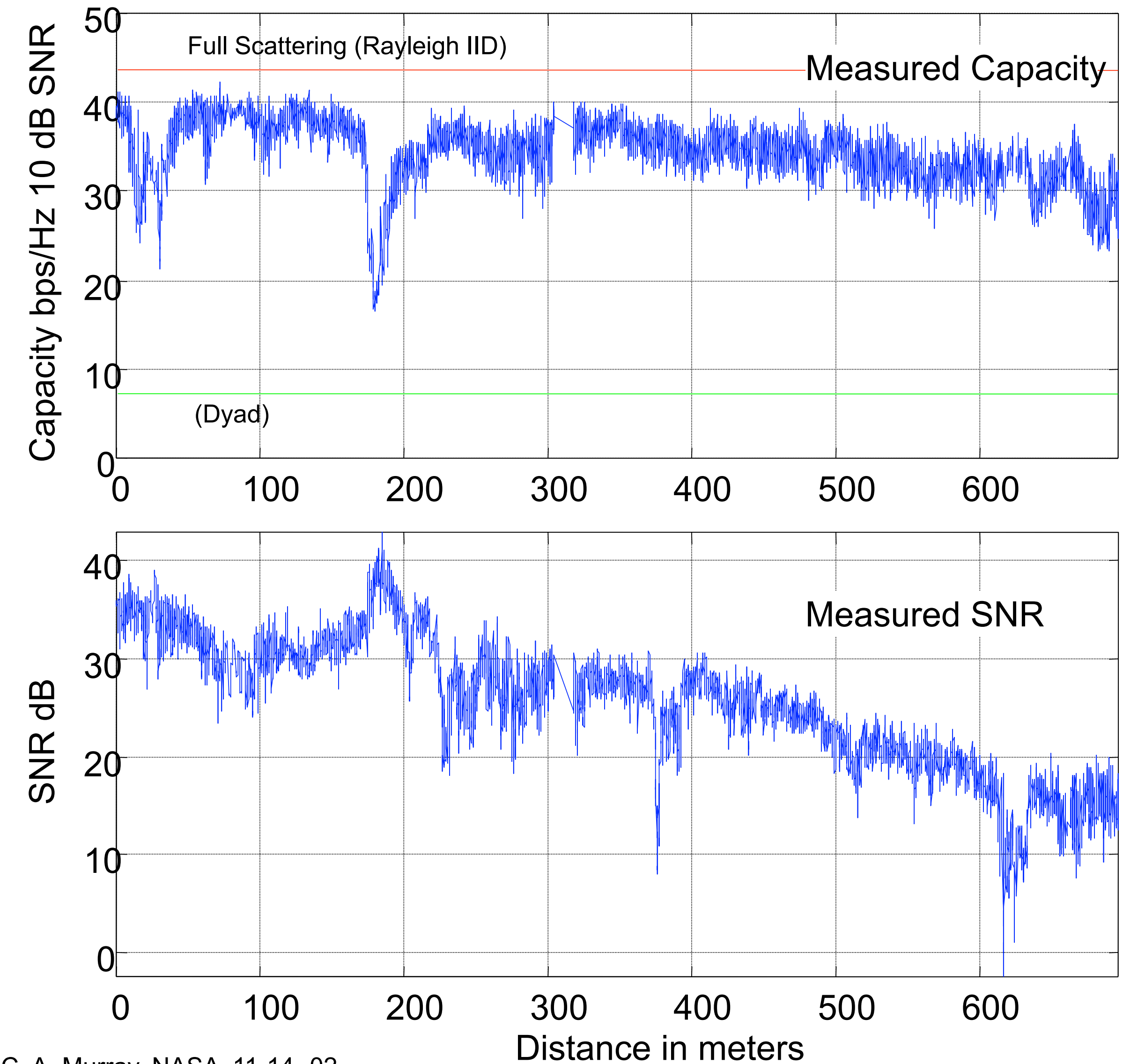

- Different data sub-streams are transmitted from different antennas
- Signal processing at the receiver separates the received signals

# Bandwidth Efficiency Improvement: BLAST Versus Diversity

## Efficiency achieved with 90% probability in bps/Hz or, equivalently, in Mbps/MHz



## Measured Manhattan Capacity & SNR for a Single Drive Run

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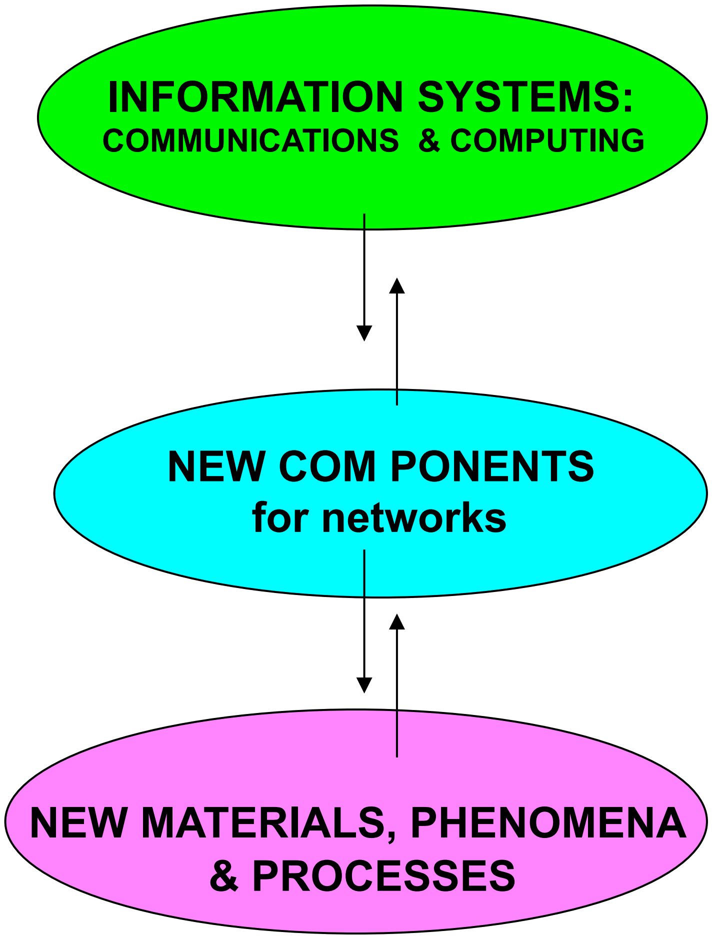
- 16 Tx 16 Rx
- 10 dB System SNR
- Max 43 bps/Hz (Rayleigh IID)
- Min 7 bps/Hz (Dyad)

## PHYSICS RESEARCH FOR INFORMATION and COMMUNICATIONS SYSTEMS

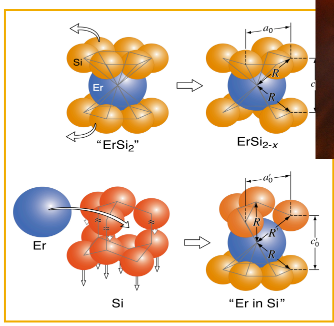


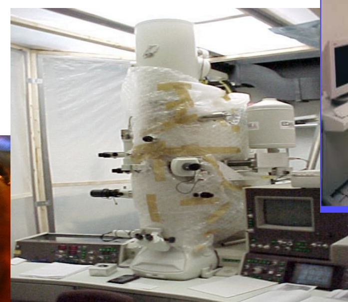

**PHYSICAL LIMITS OF COMMUNICATIONS**
**PHYSICS OF TRANSMISSION MEDIA**
**PHYSICS OF INFORMATION PROCESSING: BIOLOGICAL COMPUTATION, QUANTUM COMPUTATION**

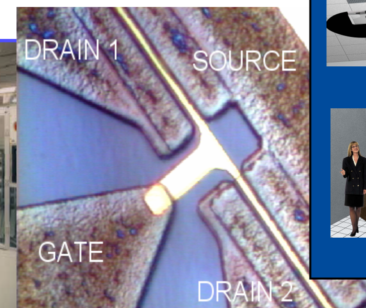
**NONLINEAR OPTICAL COMPONENTS**
**PHOTONICS BASED ON ORGANIC MATERIALS**
**SEMICONDUCTOR COMPONENTS**

**NEW PHOTONIC & ELECTRONIC MATERIALS**
**NEW PATTERNING TECHNIQUES**
**NANOTECHNOLOGY**

# Materials Research Infrastructure Hierarchy






**Physical phenomena**
simulations and modeling
quantum mechanics
correlated electrons
structure

**Materials Synthesis**
Molecular Beam Epitaxy
pulsed laser deposition
sputtering, evaporation
molecular synthesis
stamping
high pressure furnace

**Advanced characterization**
STEM, TEM, SEM,
SET, AFM, SCVM,
x-ray, endoscopy,
RF, IR, optical,
spectroscopy,
ultra-fast optics
high-speed electronics
(network analyzer)

**Processing**
Clean room,
etching,
RTA
e-beam and
optical lithography,
Nanotechnology
Center

**Devices and Components**
GaN HEMT,
150 GHz HBT
TDC, MEMS,
…

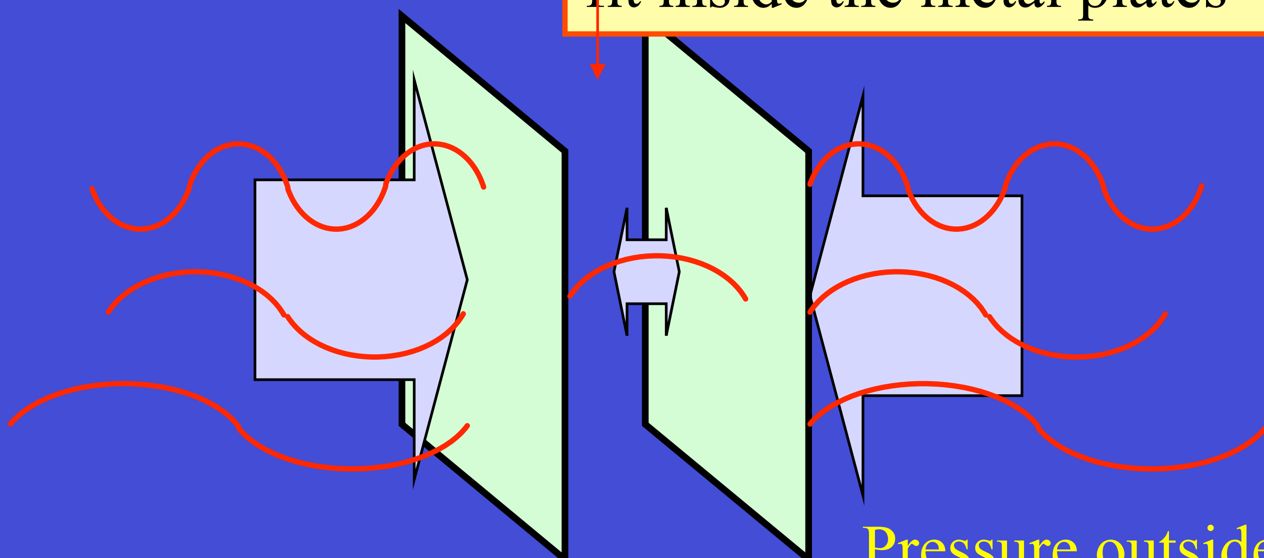
**Sub-systems and Systems**
basestations,
Ocelot,
λ-Router,
Wirless ad-hoc networks,
All-optical networks,
…

# Casimir force

Vacuum is not empty in quantum mechanics: it teems with virtual particles (photons, etc) appearing and disappearing.

Even at absolute zero, vacuum contains zero-point energy, due to fluctuations of the electric and magnetic fields.

Only short wavelengths can fit inside the metal plates



Pressure outside is higher than inside
$\Rightarrow$Casimir force of attraction

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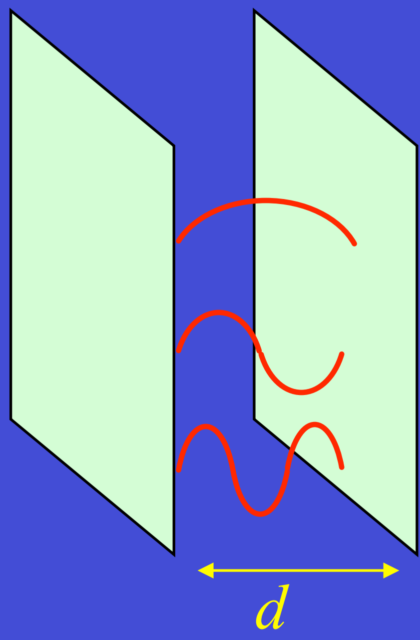



Casimir force between conducting surfaces:

$$F_{Casimir} = -\frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

Quantum effect due zero-point fluctuations on a macroscopic system

Between 2 μm thick silicon plates.

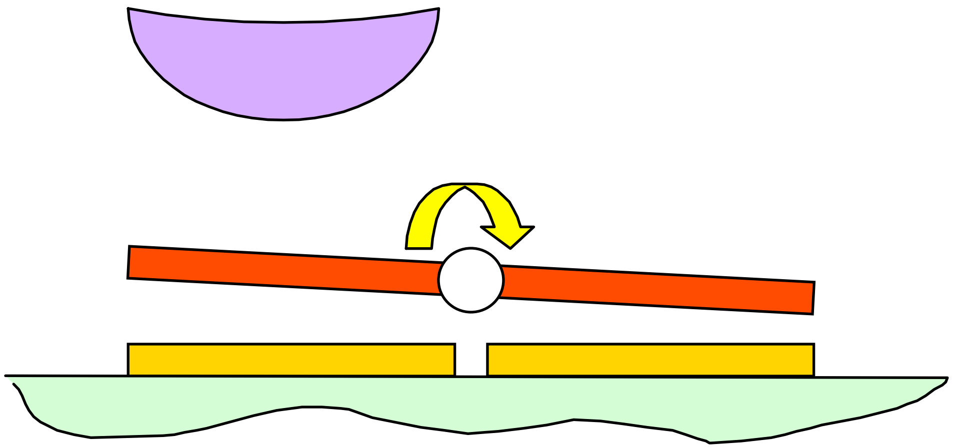
At $d$ = 1 μm, $F_{Casimir}$ ~ gravitational attraction

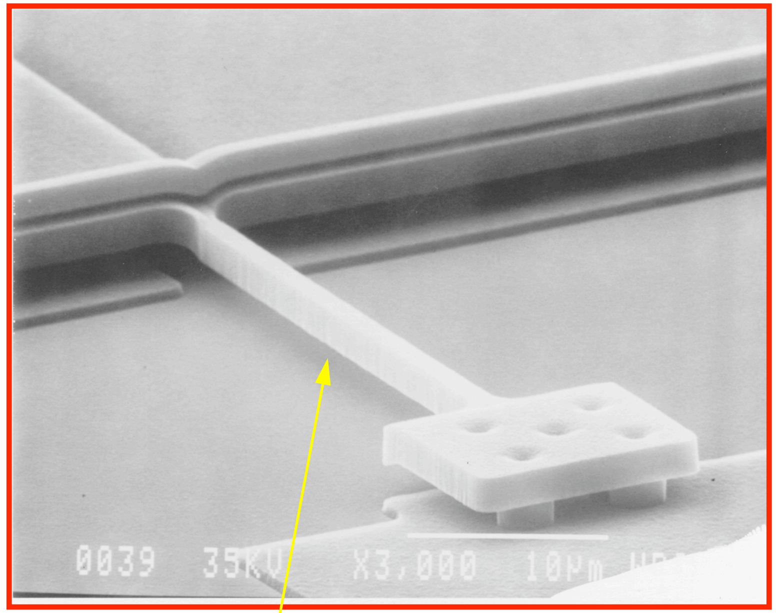
At $d$ = 10 nm, $10^8$ times larger,

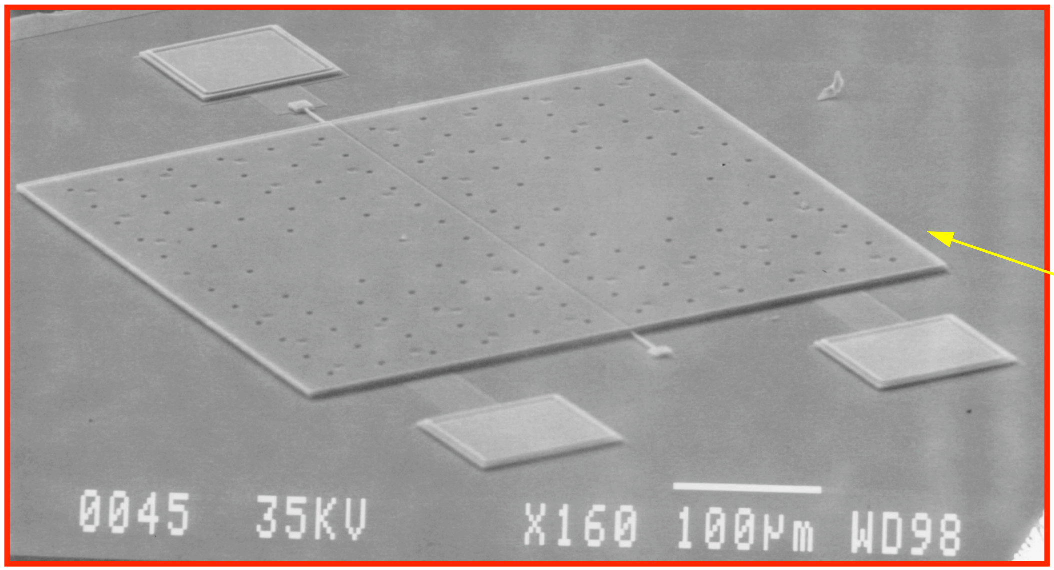
$F_{Casimir}$ ~ 1 atmosphere of pressure.

Non-ideal surfaces: finite conductivity, roughness

# MEMS SEE-SAW ACTUATED BY CASIMIR FORCE



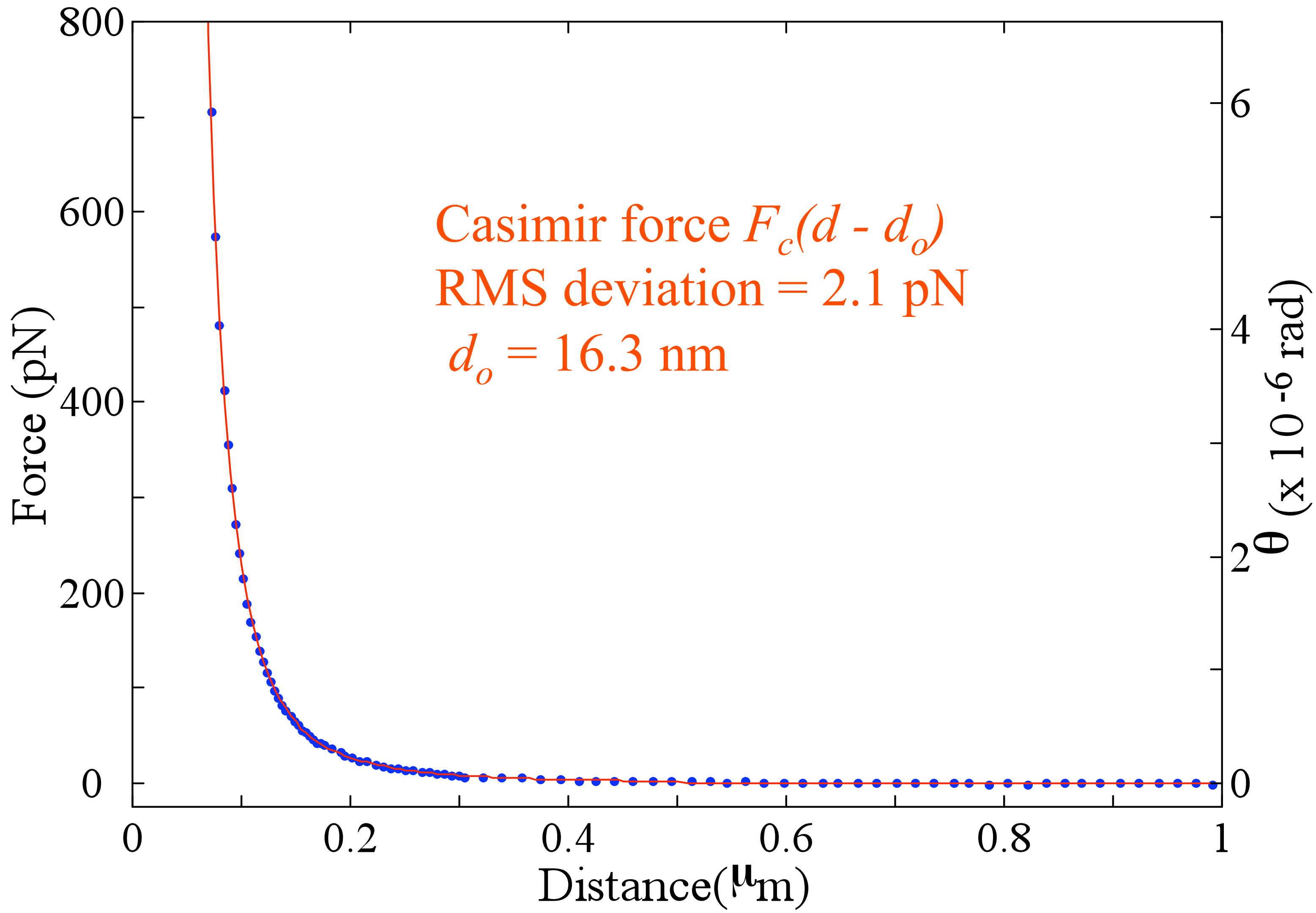



Torsional rod
cross section: 1.5 x 2 μm$^2$

poly-Si plate:
500 μm x 500 μm x 3.5 μm

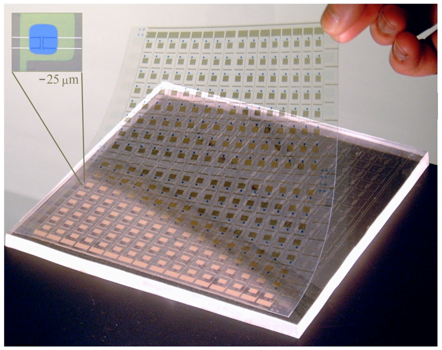
# Casimir force with roughness and finite conductivity corrections

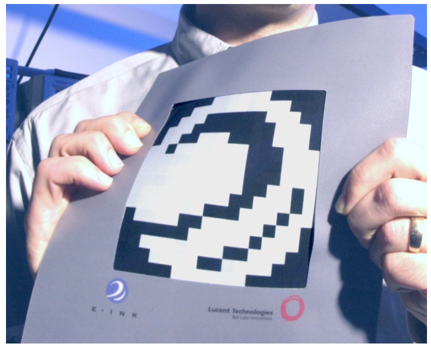


# Nanotechnology & Soft Materials Physics

## Plastic Electronics

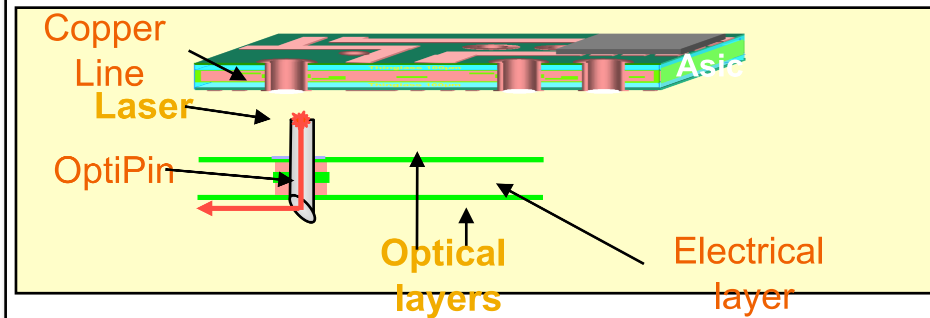
*Electronic Paper-like Displays*



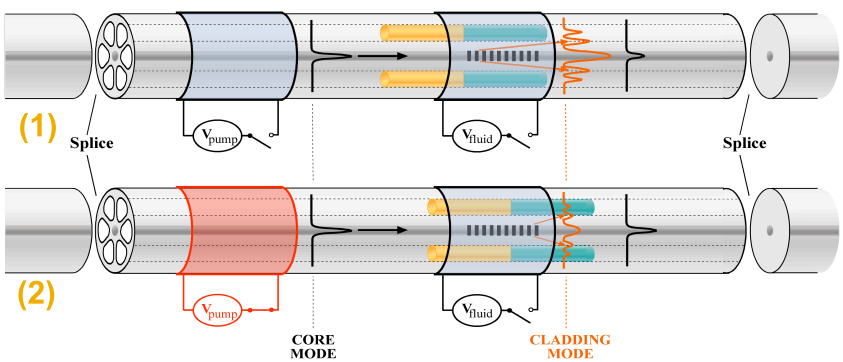
## Optical Backplanes

*Polymer Materials*



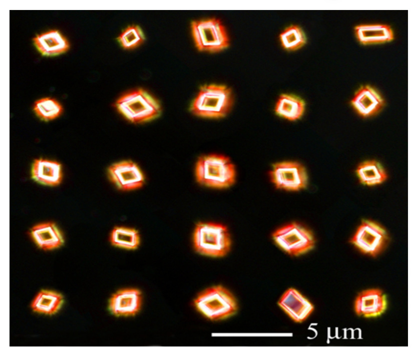

## 'Soft' Photonic Systems

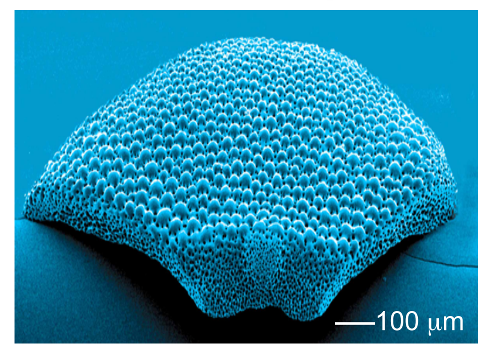
*Microfluidic Waveguide Optics*




## Biomimetics

*Controlled Crystallization & Bio-Optics*

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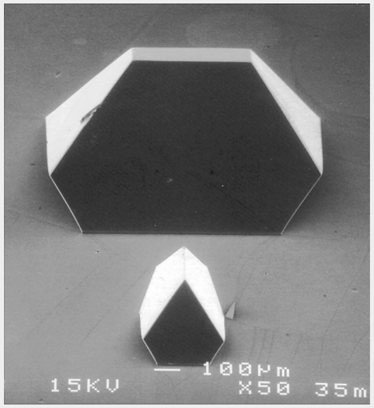
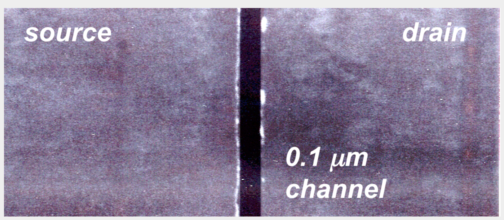
Lucent Technologies
Bell Labs Innovations

# New Techniques for Micro/Nanofabrication

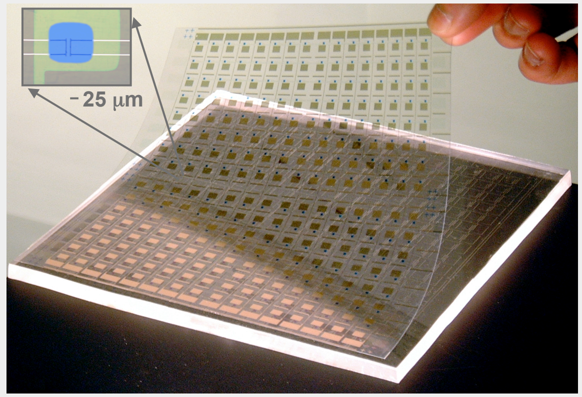
## Re-Entrant Molding



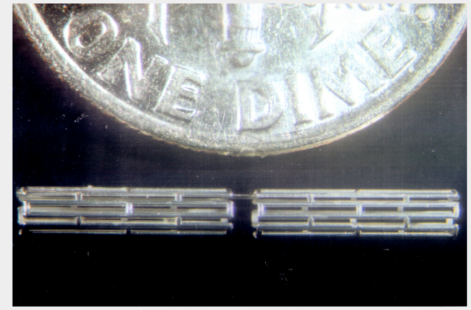

## Organic Nanotransistor using Rubber Near Field Lithography



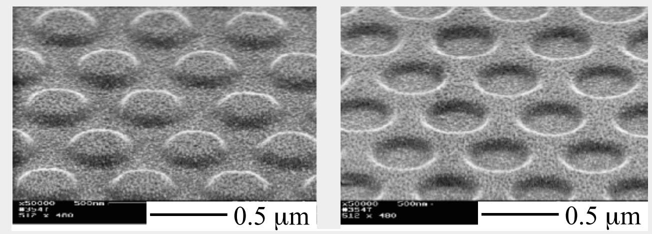

## Rubber Stamped Plastic Circuits for Electronic Paper Displays




## Printed 3D Microstructures

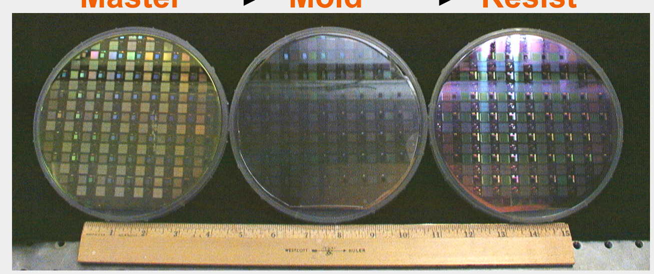



## Molded Sol-Gel Photonic Crystals

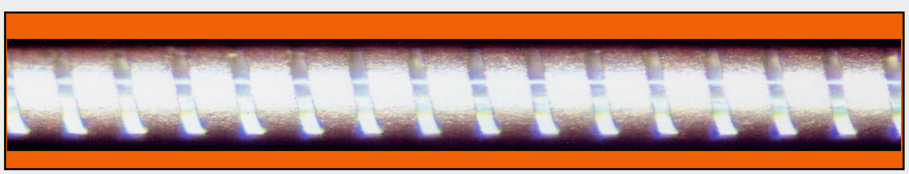



## Full-Wafer Molding of Thin Resists

Master → Mold → Resist



## Printed On-fiber Actuators for Tunable Fiber Devices



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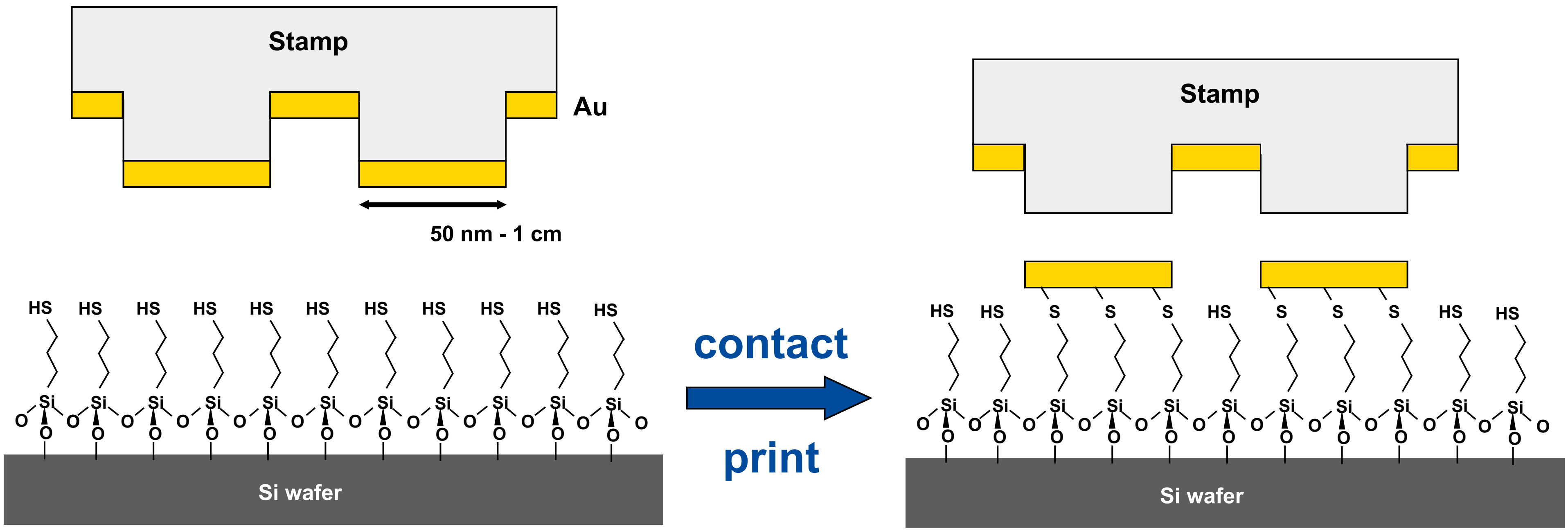
C. A. Murray, NASA 11-14 -02

Lucent Technologies
Bell Labs Innovations

# Nanotransfer Printing: SAMs as Molecular Scale Adhesion Layers




- Resolution: ~5-10 nm
- Simple, low cost, etc.
- Purely Additive
- Compatible w/ many materials

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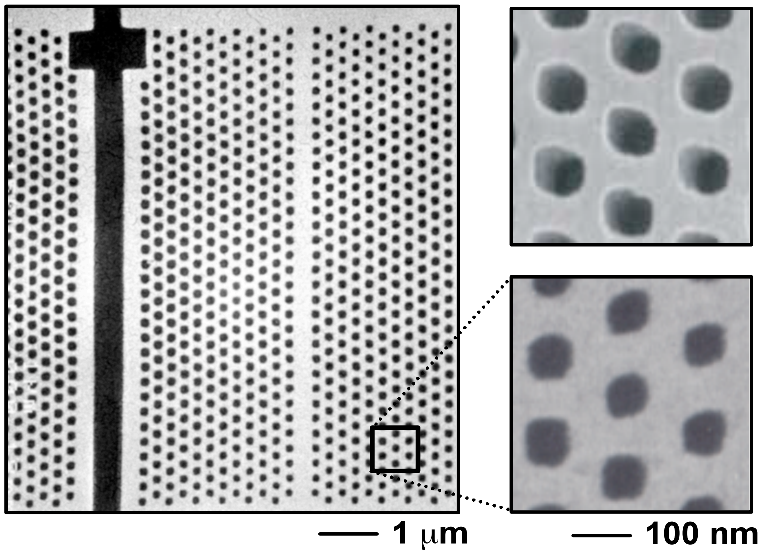
## Nanotransfer Printing: Nanometer Resolution

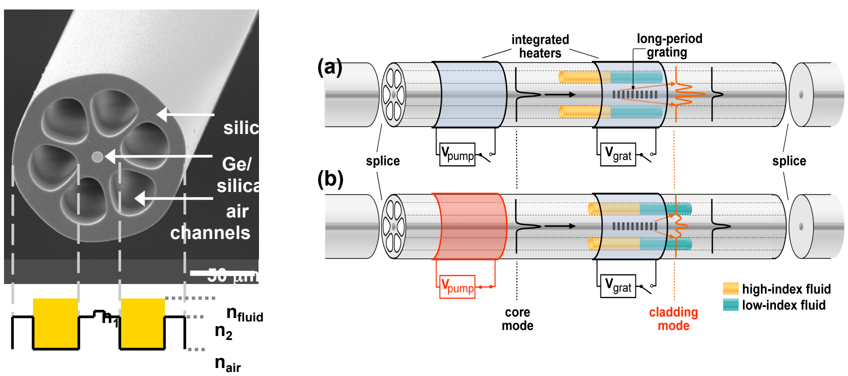



stamp

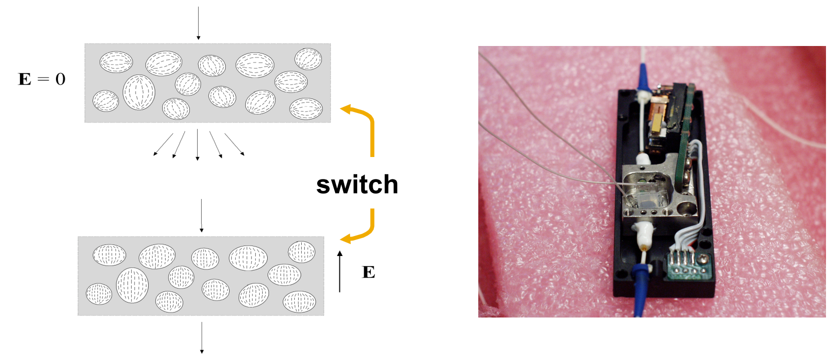
printed pattern

# Optical Network Applications for 'Soft' Materials

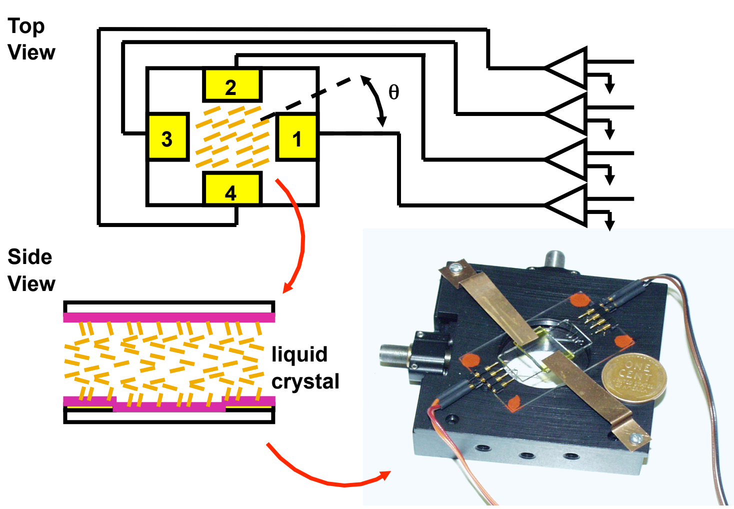
## Microfluidic Tunable Fiber for DGEFs



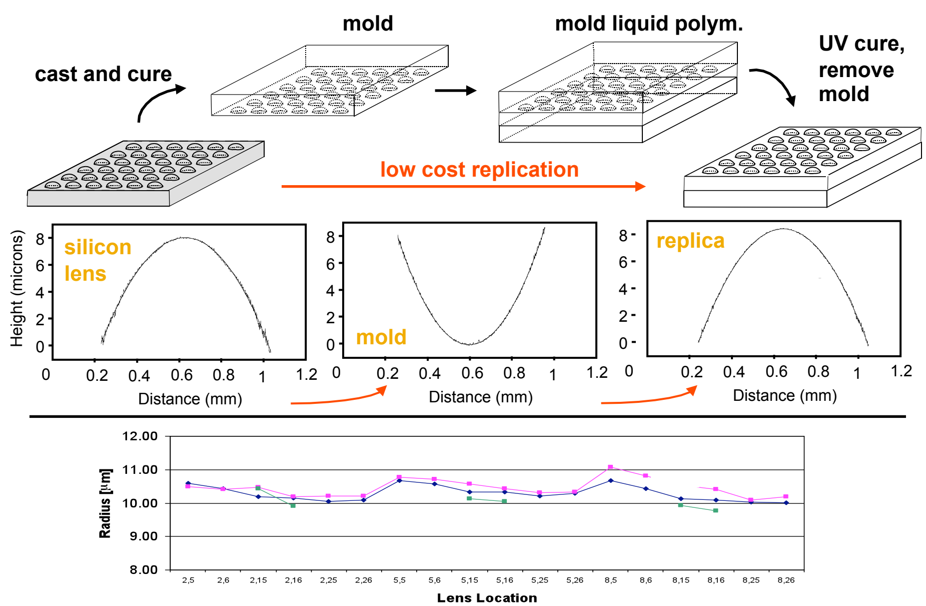

## Polymer Dispersed LC VOAs




## LC Polarization Controller for PMD Comp.

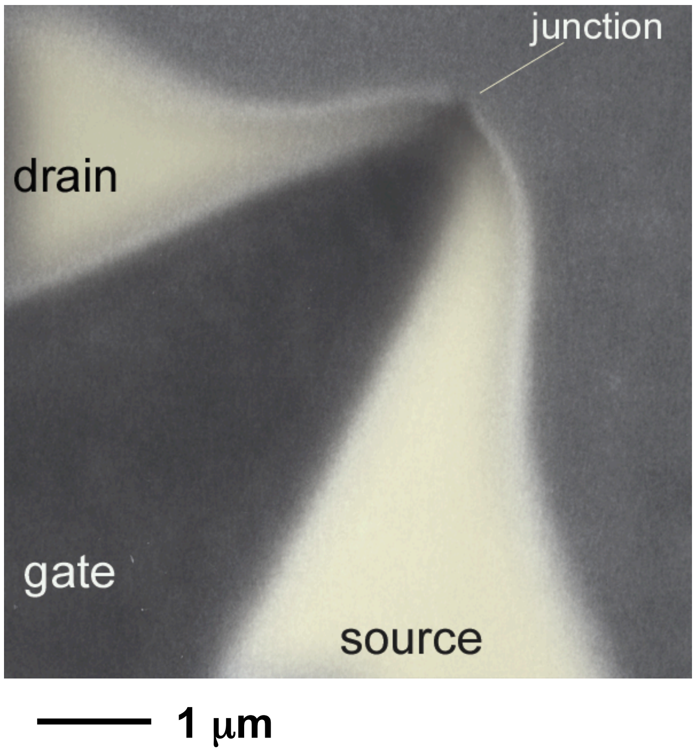



## Low Cost Microlens Arrays

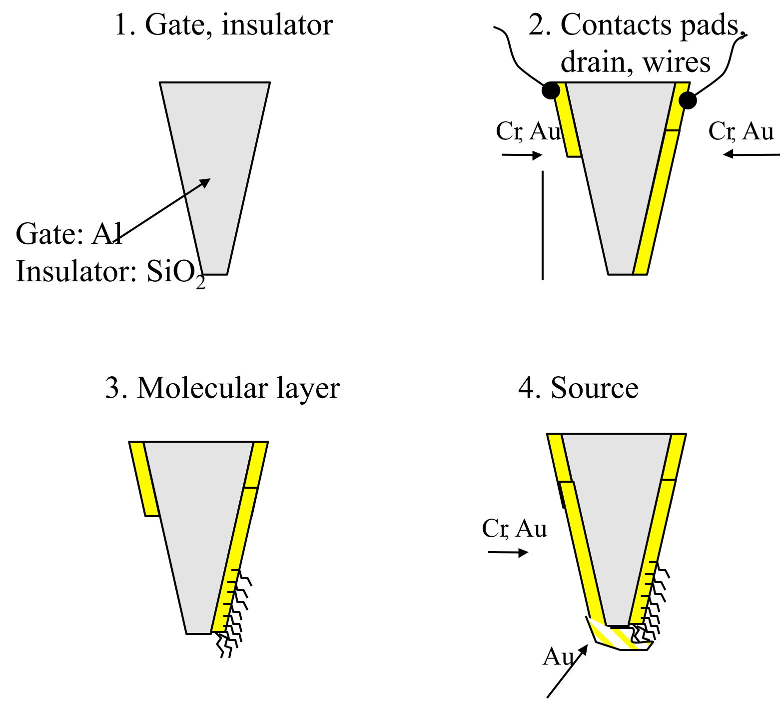


# Molecular Transistors-On-a-Tip

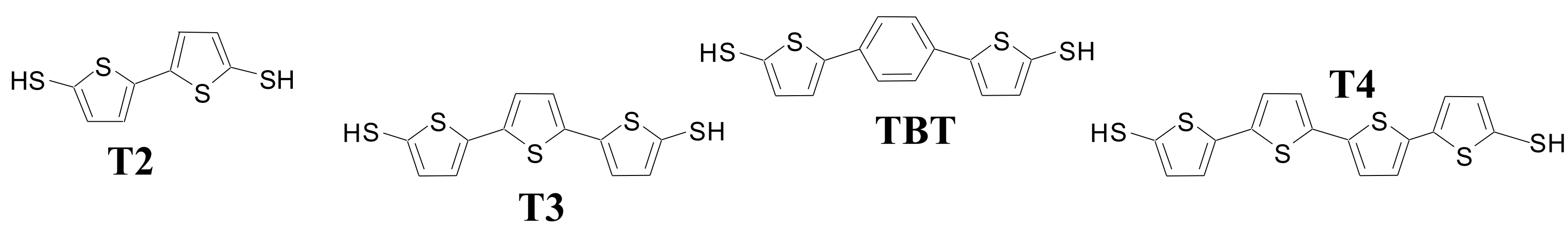
## Scanning Electron Micrograph




## Fabrication Steps




## Materials

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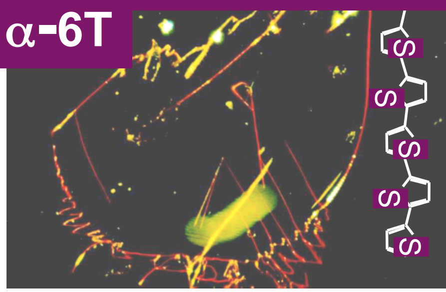
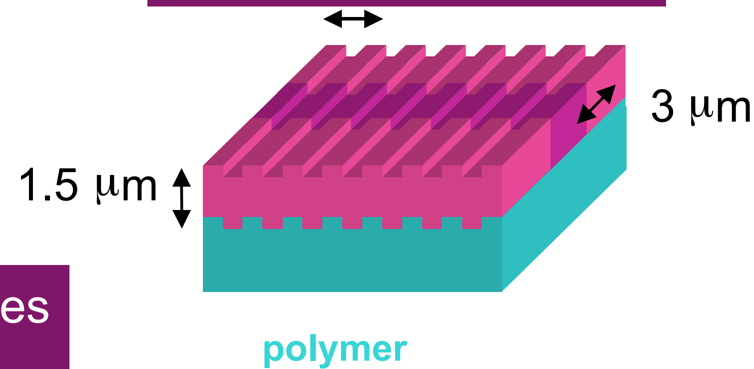
# New Materials in Physical Research

## Organic Semiconductors

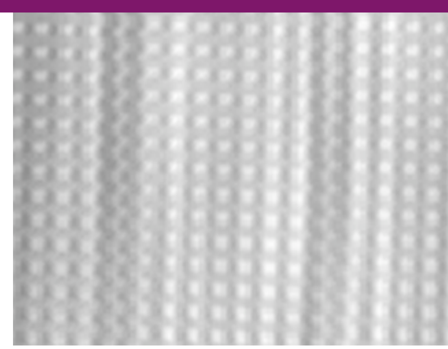
$\alpha$-6T




## Chalcogenide Glasses

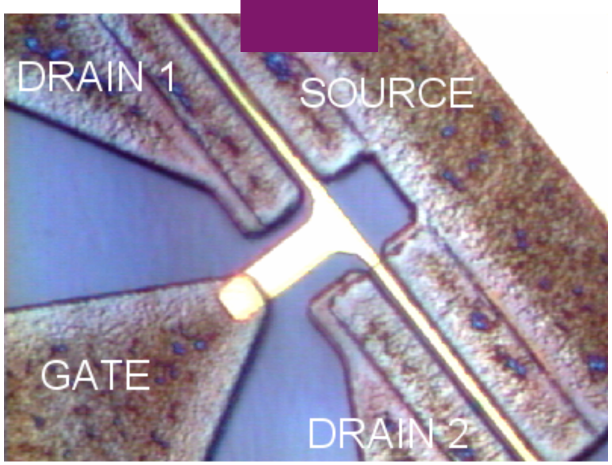



## Oxide Heterostructures

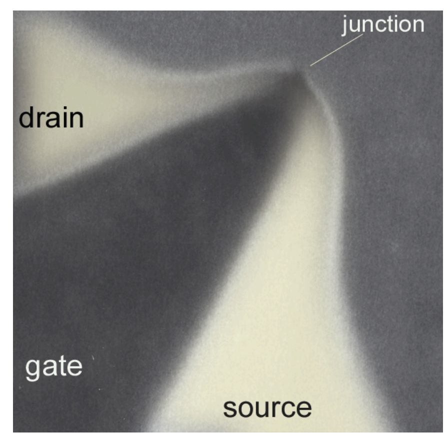


$(SrTiO_3)_{5u.c.}/(LaTiO_3)_{2k\ u.c.}$

## GaN

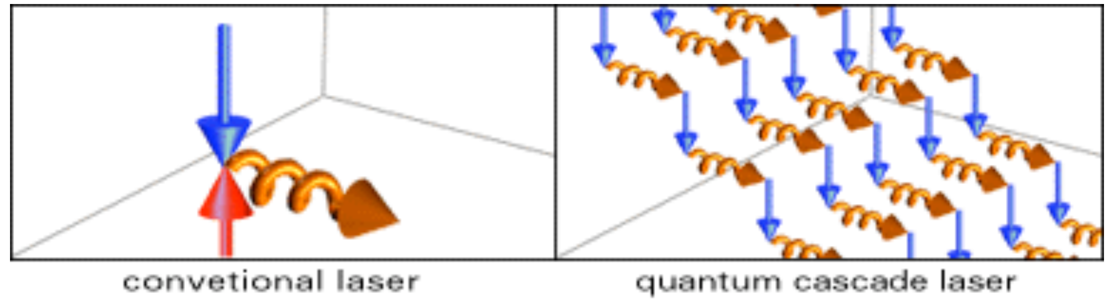



## STM Transistor

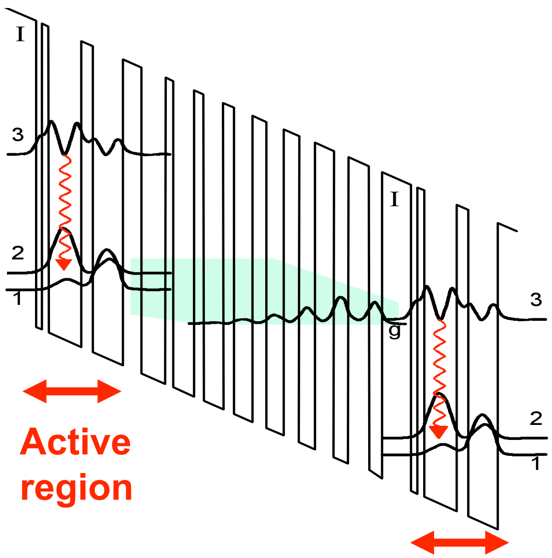



1 μm

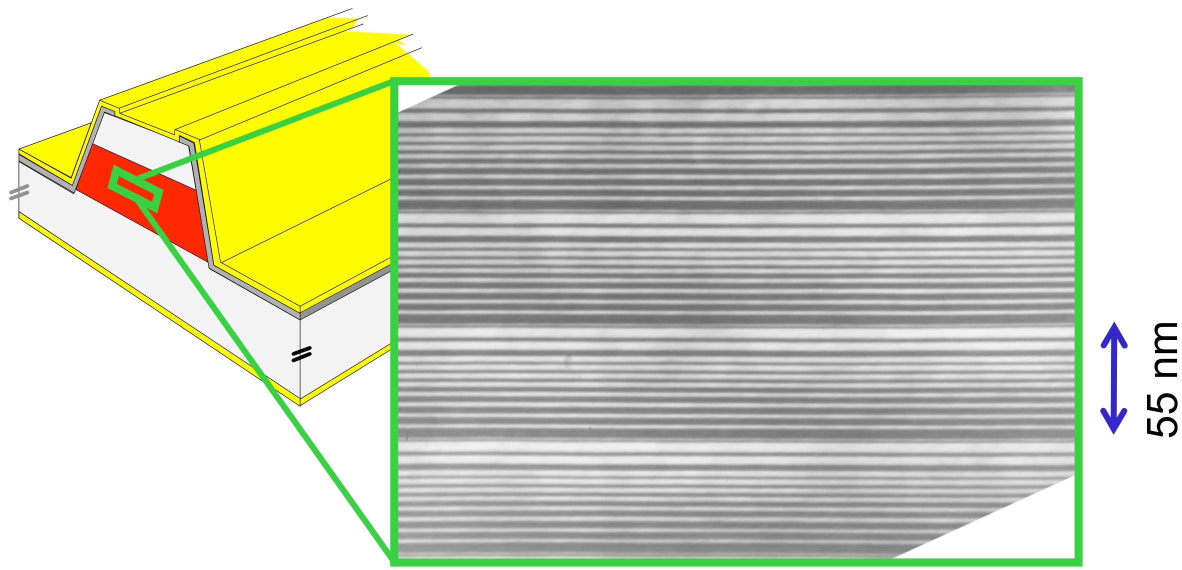
# Quantum Cascade Lasers

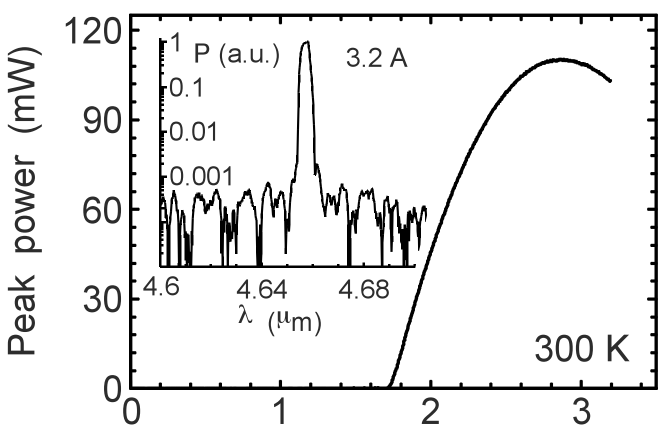



*Designed by "band-structure engineering"*




*Grown by "molecular beam epitaxy"*



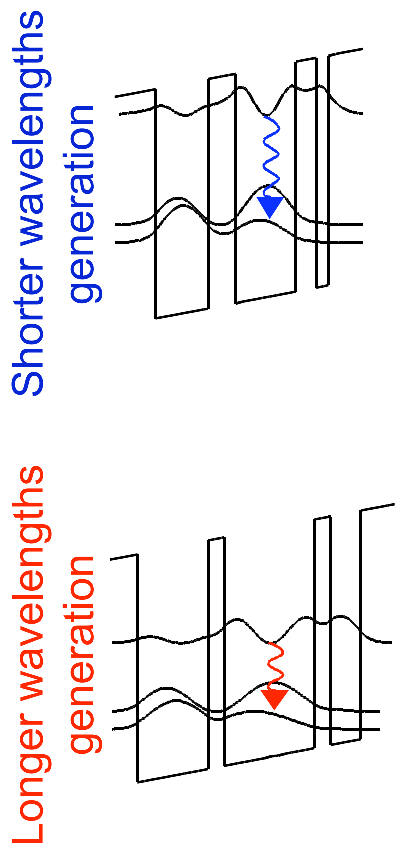



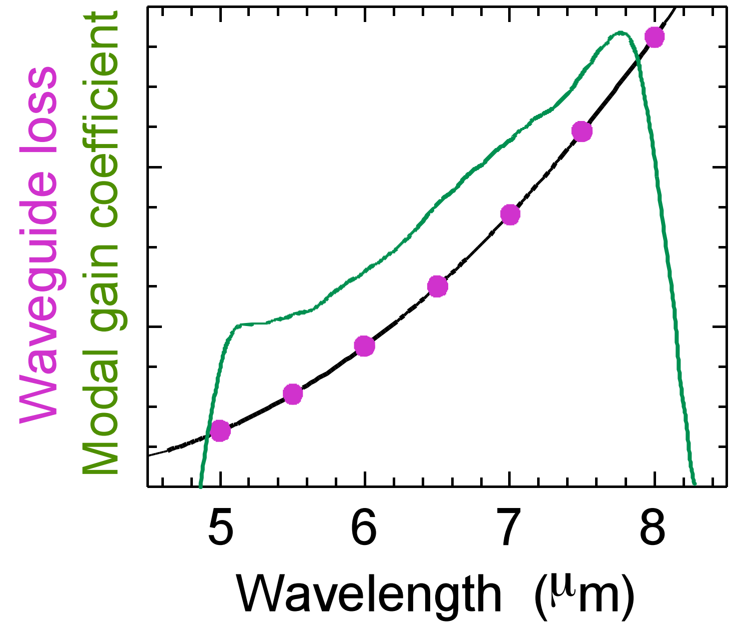

C. A. Murray, NASA, 11-14-02

- wavelength agile, mid-infrared, single-mode, tunable, high-speed, and high power
- for mid-infrared sensing applications, and potential for free-space optical wireless

# Design of the ultrabroadband quantum cascade laser

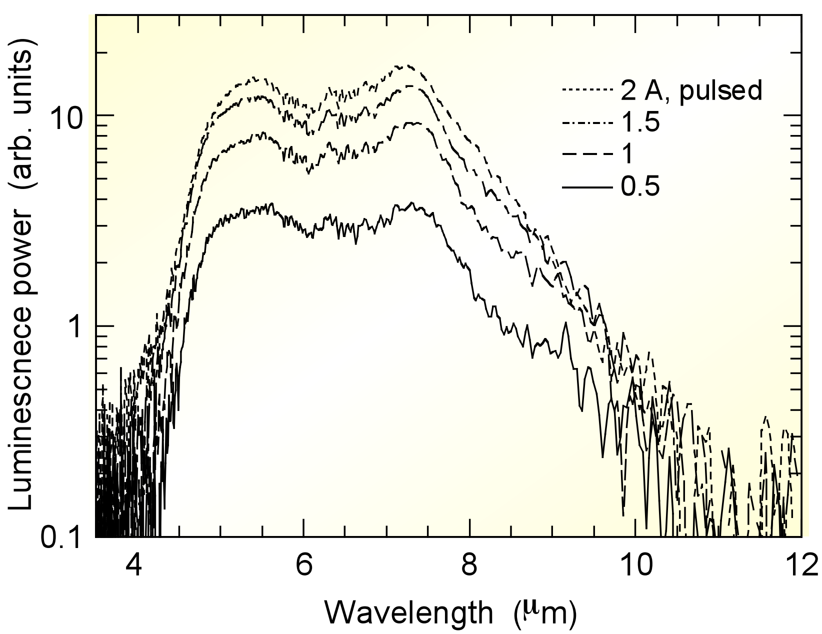

C. A. Murray, NASA 11-14 -02

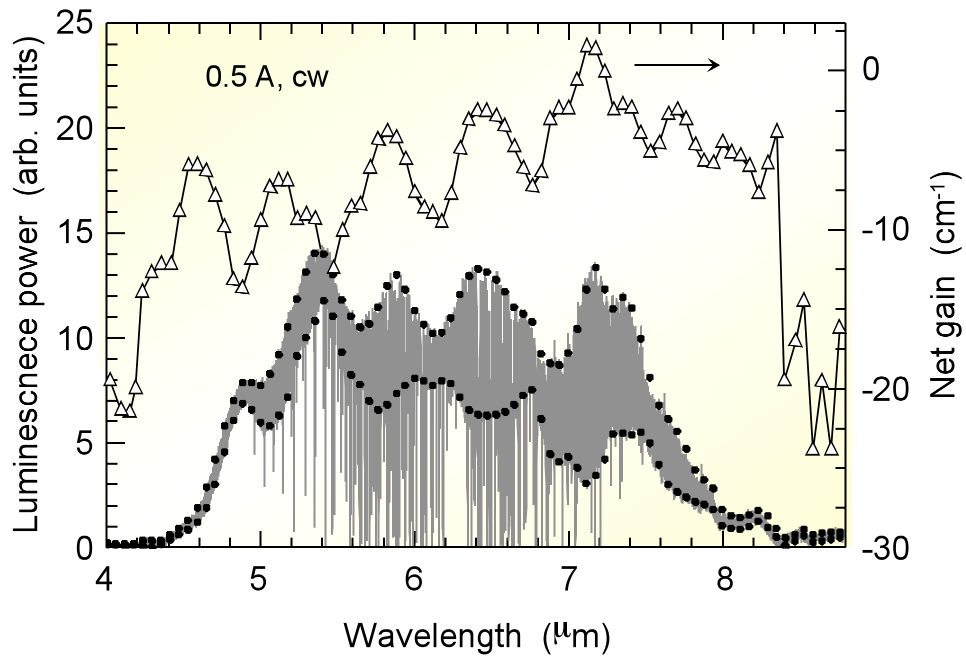



36 different stages designed:
*gain compensates loss*
over wide wavelength range

# Luminescence and gain spectra

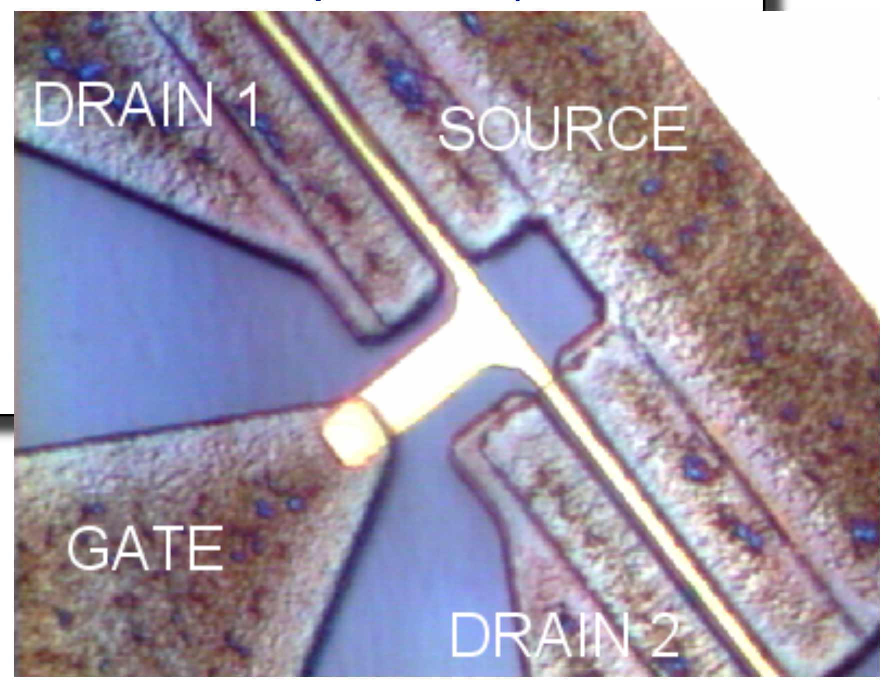



luminescence and continuous gain achieved for design wavelength range $\lambda \sim 5$ - 8 $\mu m$

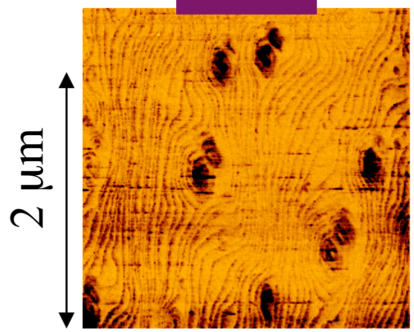
# GaN Electronics for Wireless

- high power, broadband, linear, solid state amplifiers for wireless base-stations
- 160 GHz modulator drivers for ONG (5V, several Watts)
- **Advantages**:
  - high breakdown voltages (> 100V) ⇨
  - high efficiency, Power Added Efficiency (PAE) ~ 30 - 40%
  - cutoff frequencies, $f_{max}$ > 100GHz (device design + intrinsic material parameters)
- **Where we are now**
  - $f_{max}$= 9 GHz (1.5 $\mu$m gate)
  - $V_{bd}$>100 Volts
- **Competition**
- Si LDMOS (PAE~5% eff.), w/predistortion (PAE~25% eff.)



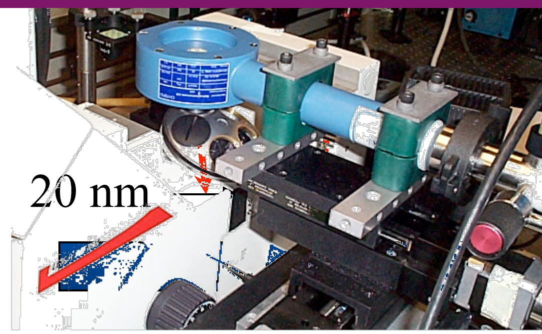
## Advanced Characterization Tools

AFM



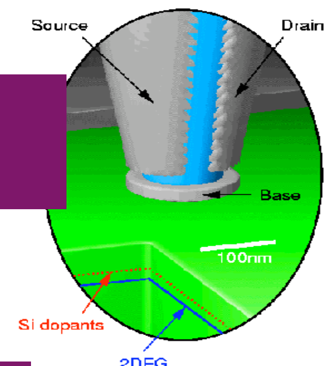

Dislocation leakage current in AlGaN/GaN

Confocal μ-Raman Spectrometer



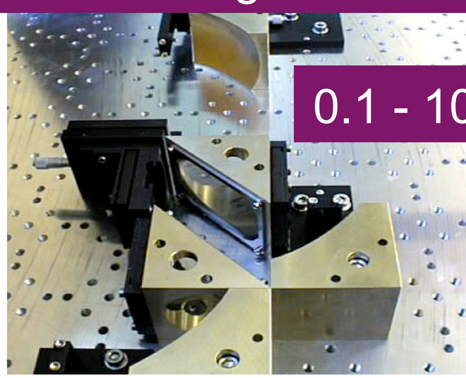

Atomic Scale Electron Spectroscopy

SET




Quasi-optic reflectance bridge

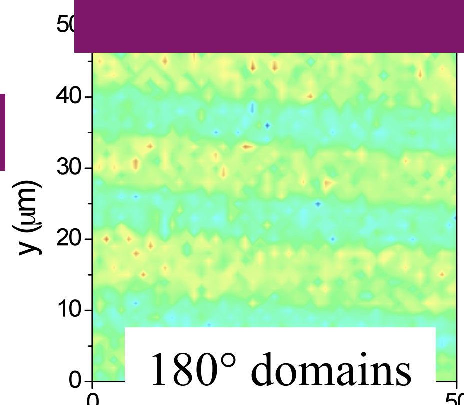
0.1 - 10 THz



New polymers for modulators

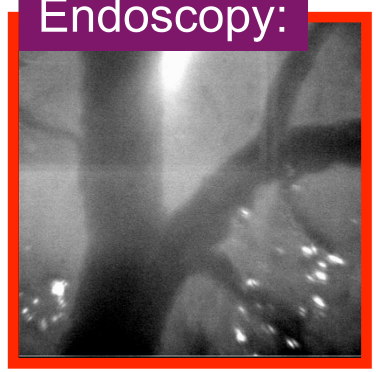
Limits to $LiNbO_3$

X-ray microscopy




180° domains in PPLN

Endoscopy:



Mapping in-vivo cellular structure/activity in the brain

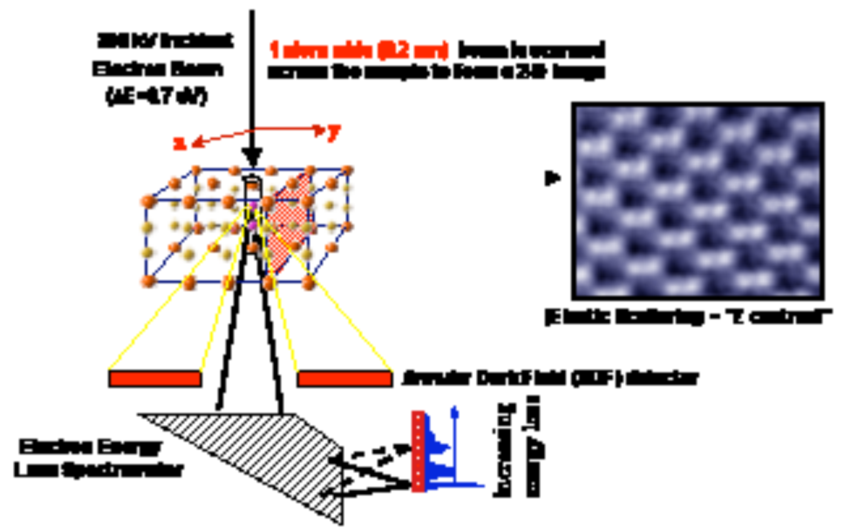
# Science meets Technology at the atomic-level

## Atomic Scale Electron Spectroscopy

The ability to identify on an atomic scale:

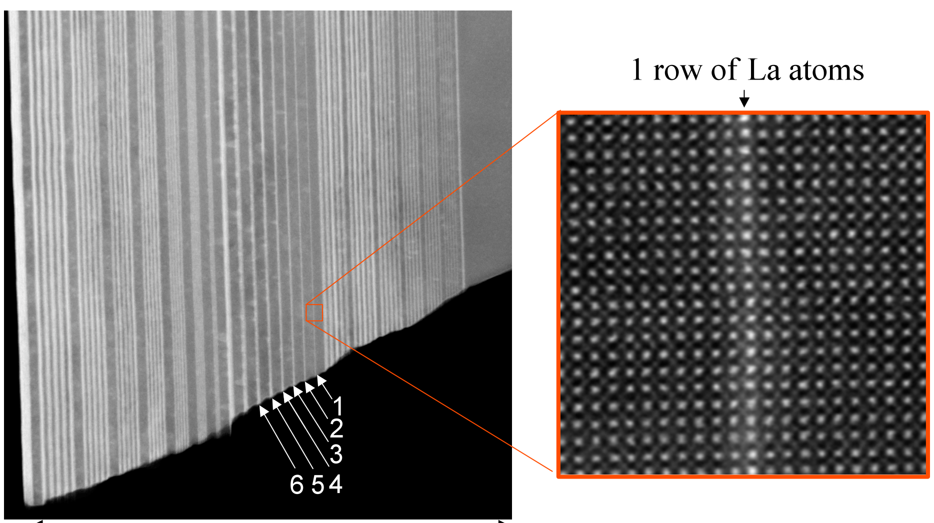
- Where each atom column is;
- What type of atoms are there;
- How they are bonded there.

### The Scanning Transmission Electron Microscope

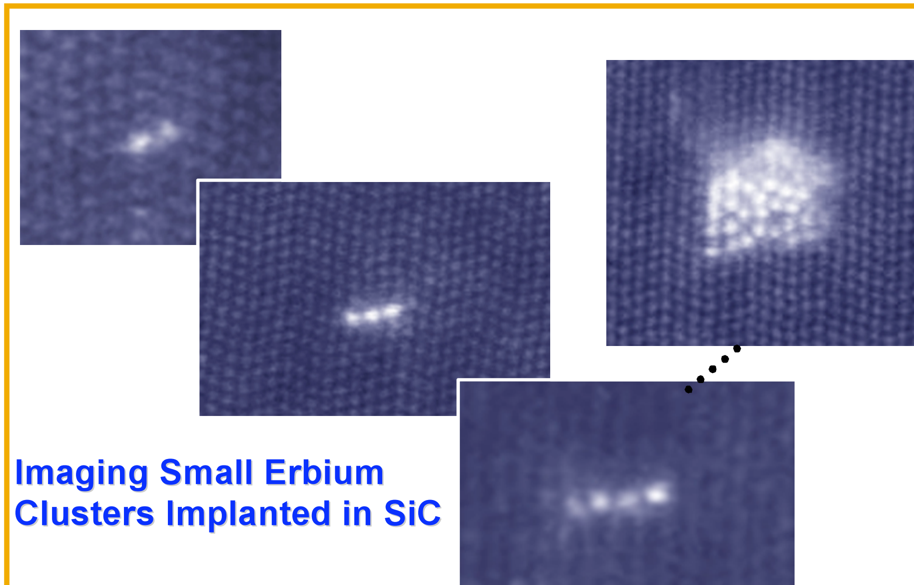


### $LaTiO_3/SrTiO_3$ : Novel Superlattices

*Atomic-Scale control of the building blocks ofNanotechnology*




1/100 of a human hair (500 nm)



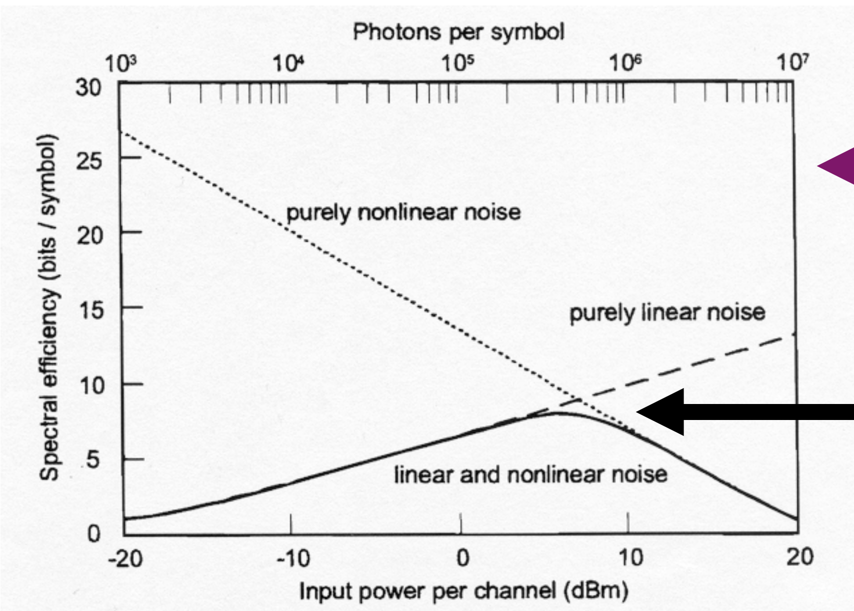
**Imaging Small Erbium Clusters Implanted in SiC**

# Shannon Capacity of Nonlinear Fiber Optics

$$I = \log_2\left[1 + S/N\right] \longrightarrow I = \log_2\left[1 + \frac{(1-\phi)S}{N+\phi S}\right]$$

Some signal power is lost

Signal turned into noise



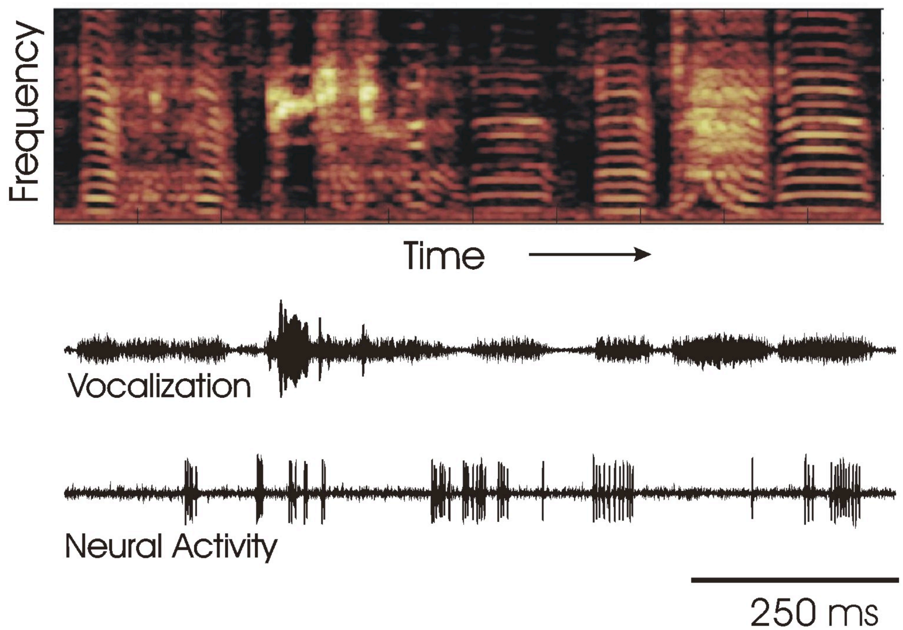

$\phi$ depends on Parameters of System (length, nonlinearity, etc). This Plot For Certain " Typical" Parameters

Gives a capacity limit for this architecture, but not necessarily a fundamental limit.

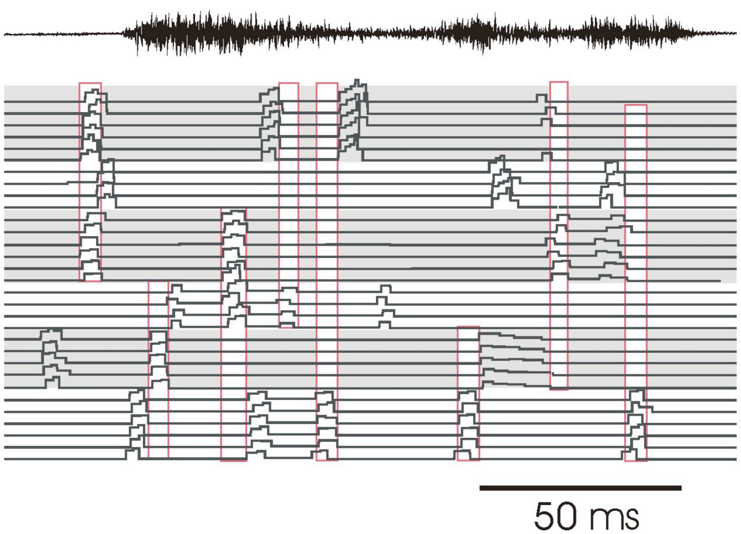
# Neural Mechanisms of Sequence Generation



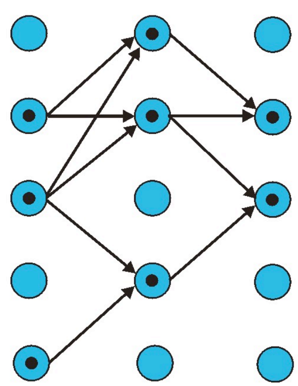
## Neural Dynamics During Songbird Vocalization




## Rapid Sequential Activation of Bursts

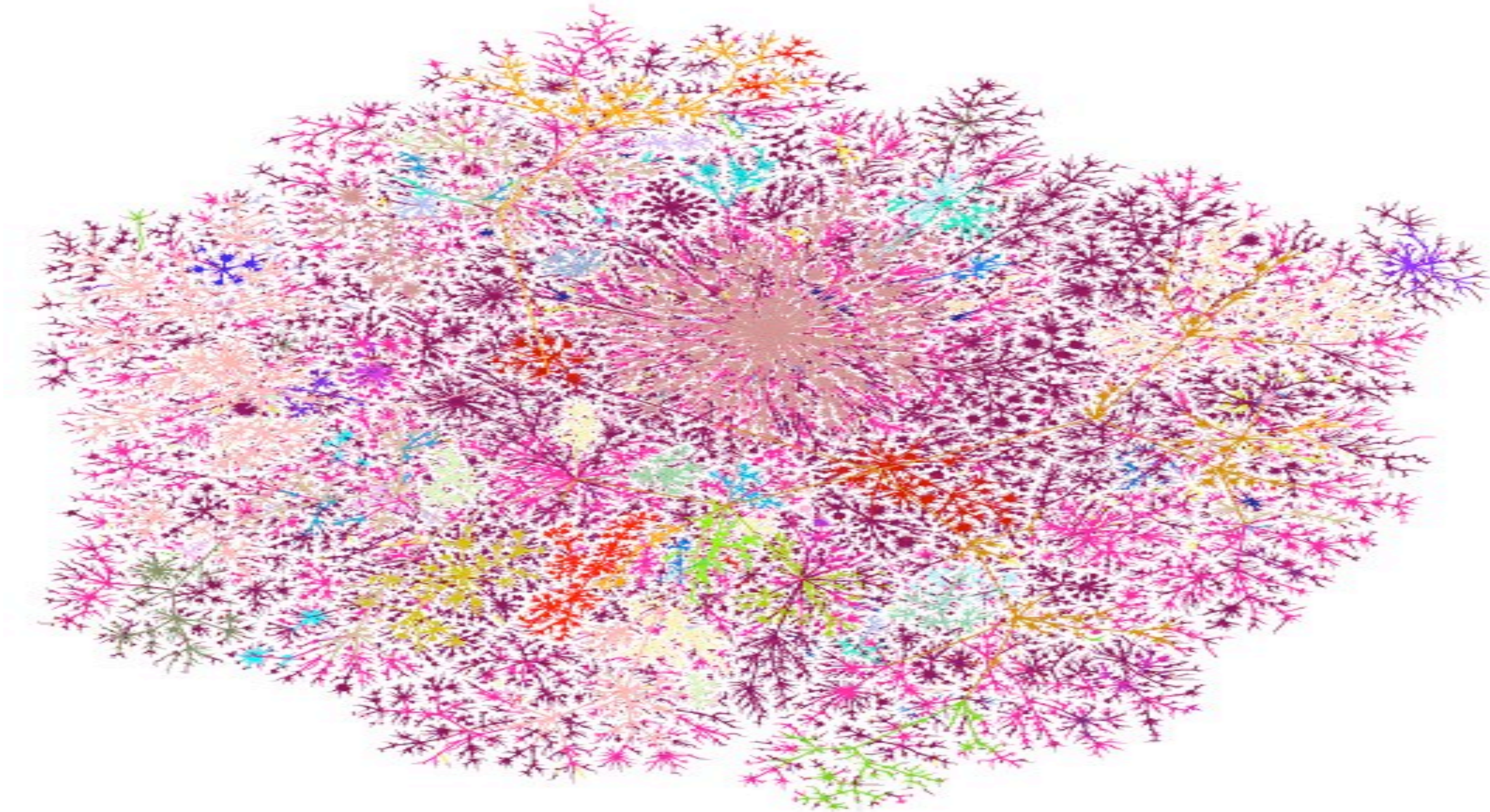



## Neural Models of Sequence Generation



## Premotor Neurons Generate Precisely Coordinated Bursts of Spikes During Vocalization

# Technology innovations are creating the foundations for next-generation networks



**100 million people will log on to the net today**